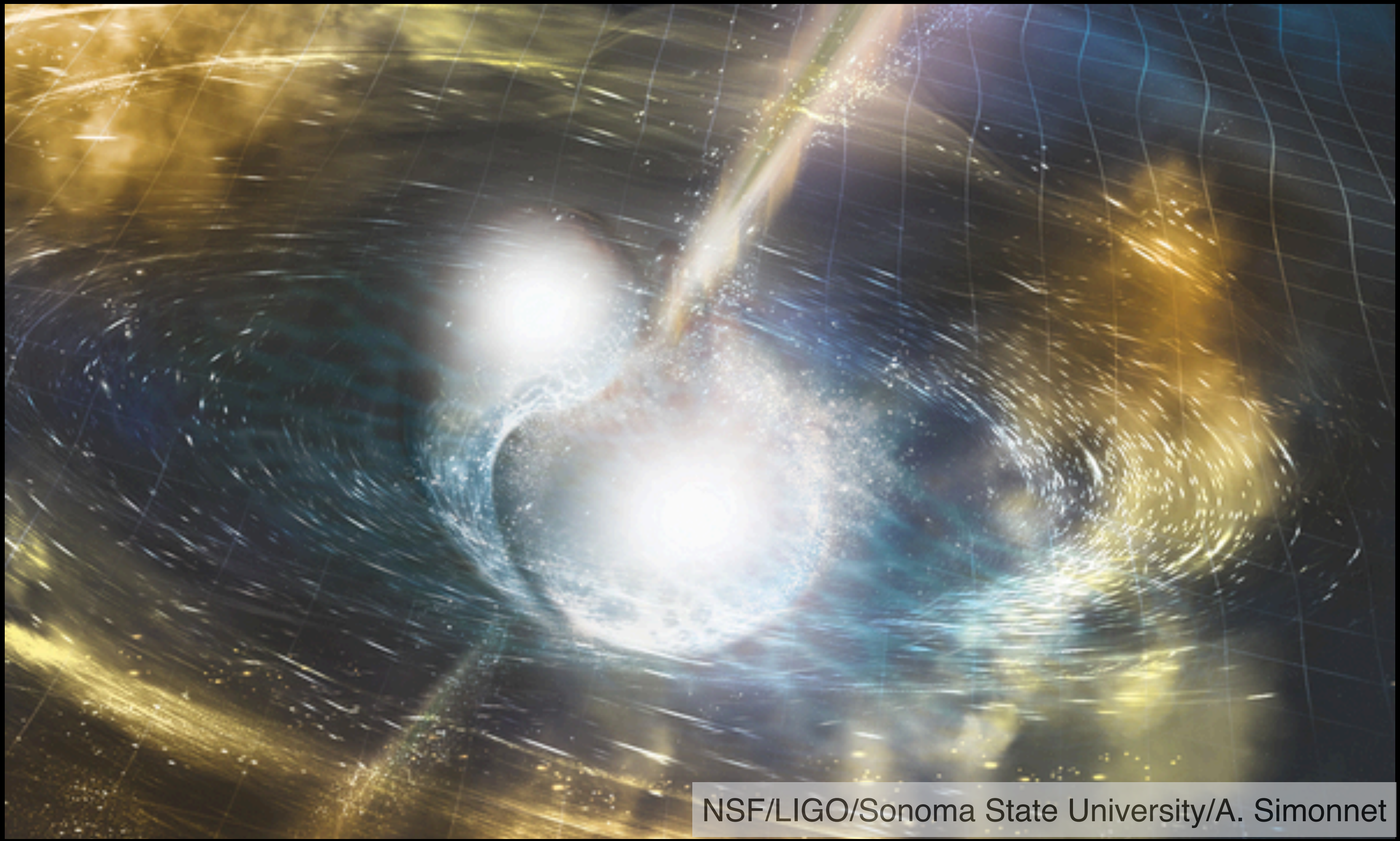
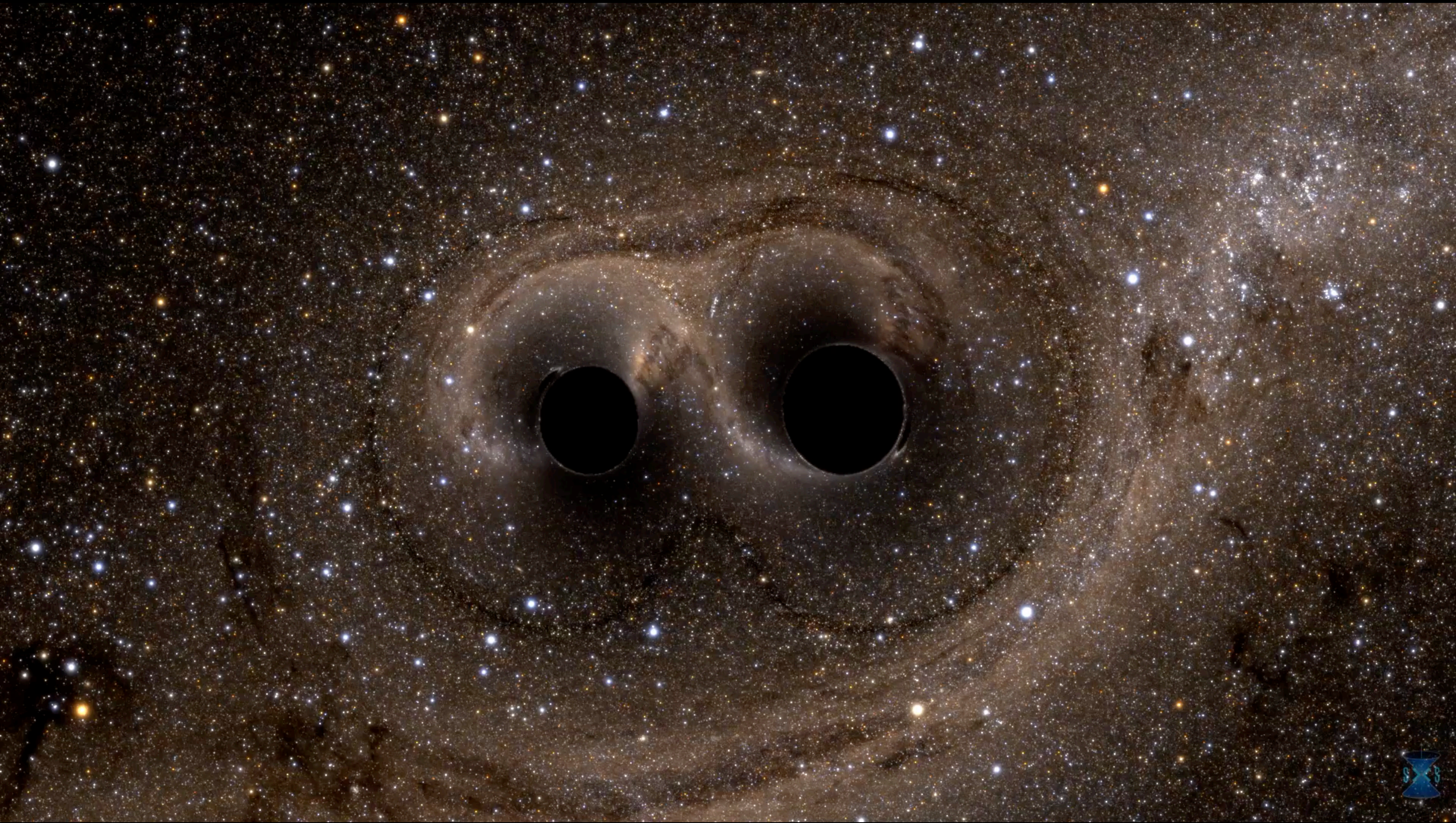
Observing black holes and neutron stars with gravitational waves



Jonah Kanner
LIGO Laboratory

LSC

Caltech



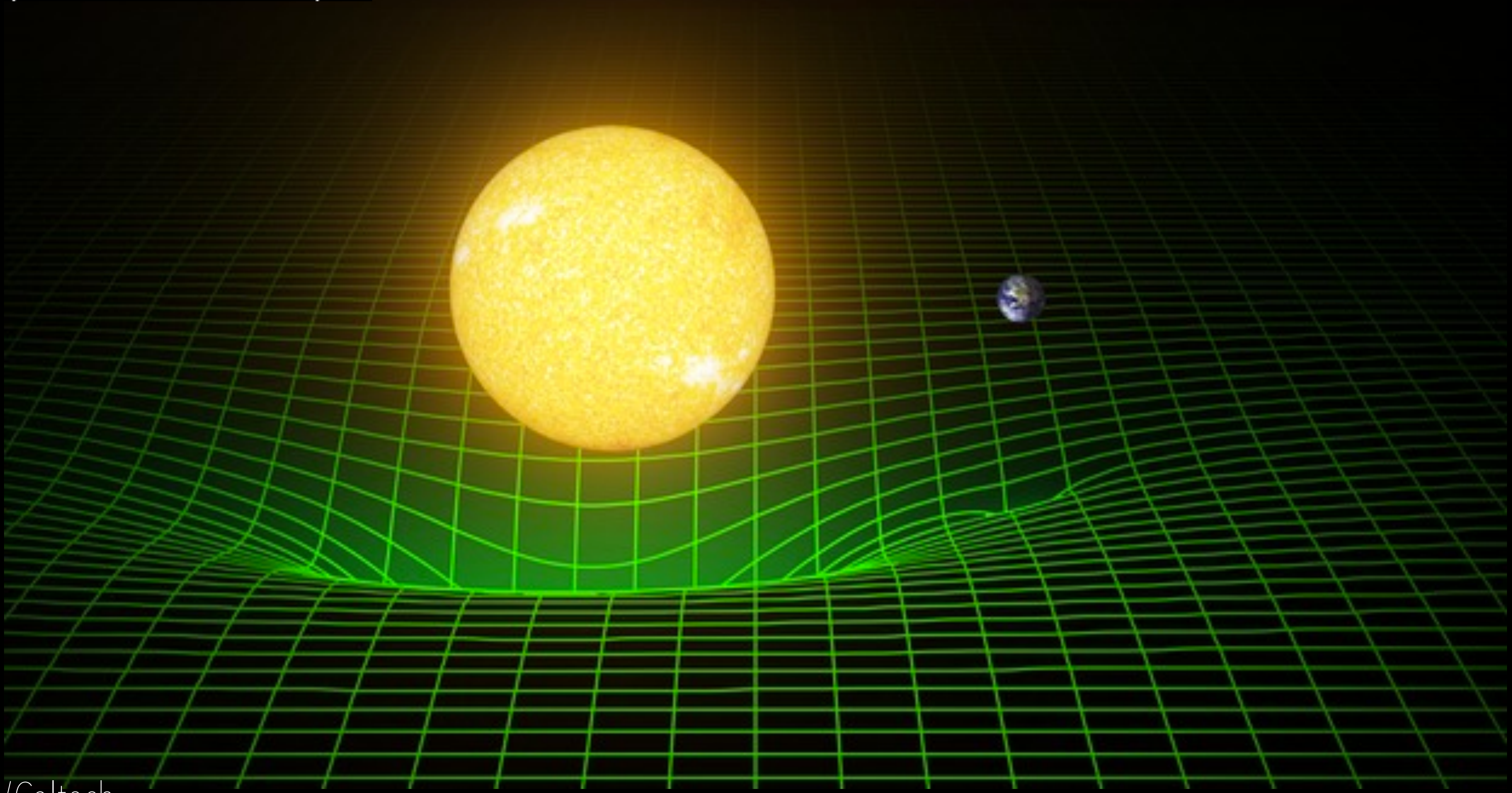
Merging Black Holes

Animation created by SXS

Einstein's Gravity: General Relativity

Matter tells spacetime how to curve
Spacetime tells matter how to move
- John Wheeler

$$G_{\mu\nu} = 8\pi\ T_{\mu\nu}$$



LIGO/Caltech

Merging Neutron Stars

Animation by NASA Goddard

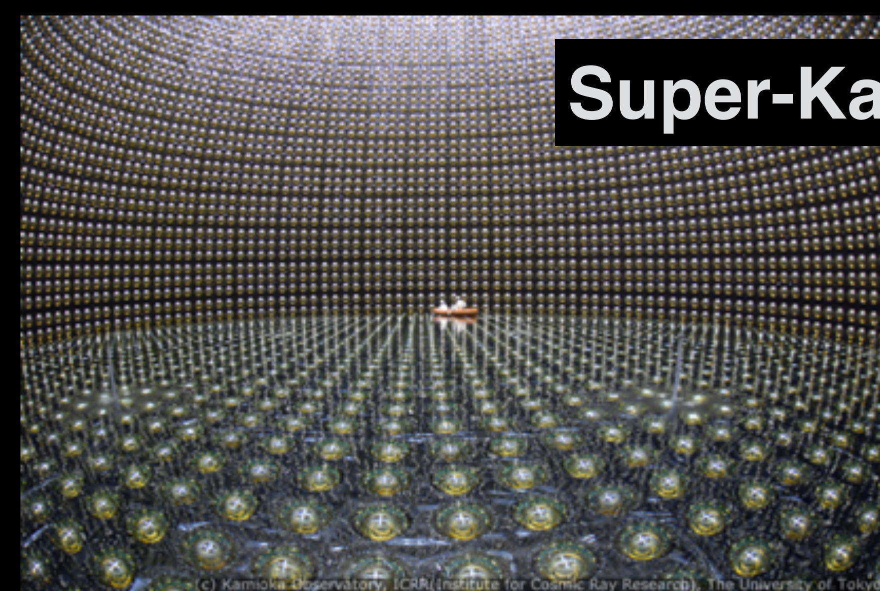
Why search for gravitational waves?

They are a completely new way to study the universe

Most of what we know about astronomy comes from photons or particles, neutrinos, or cosmic rays

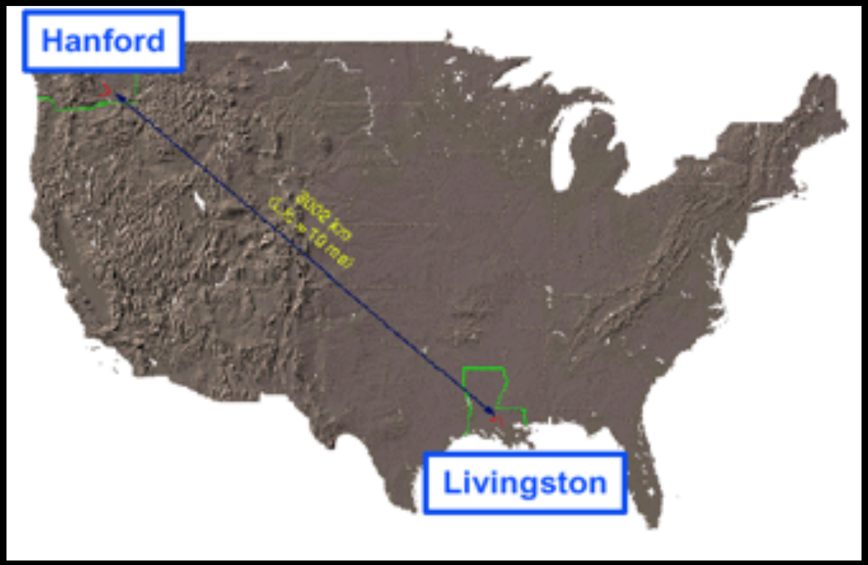
Keck Telescope

Super-Kamiokande



Gravitational waves

- are produced by the most violent events in the universe
- travel unimpeded through matter
- carry direct information about the motion of bulk matter

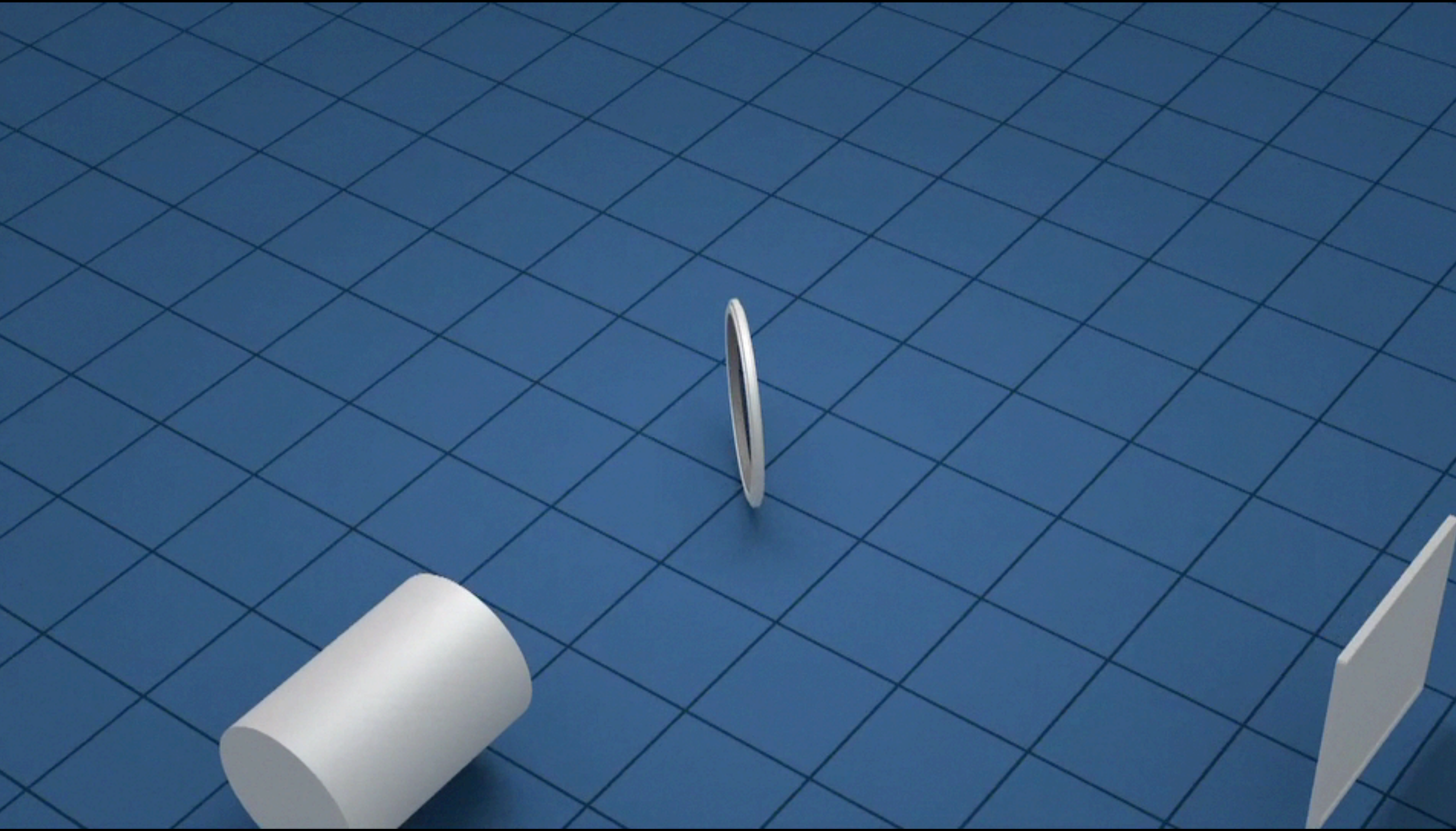


LIGO

4 km interferometers

Hanford, WA and Livingston, LA

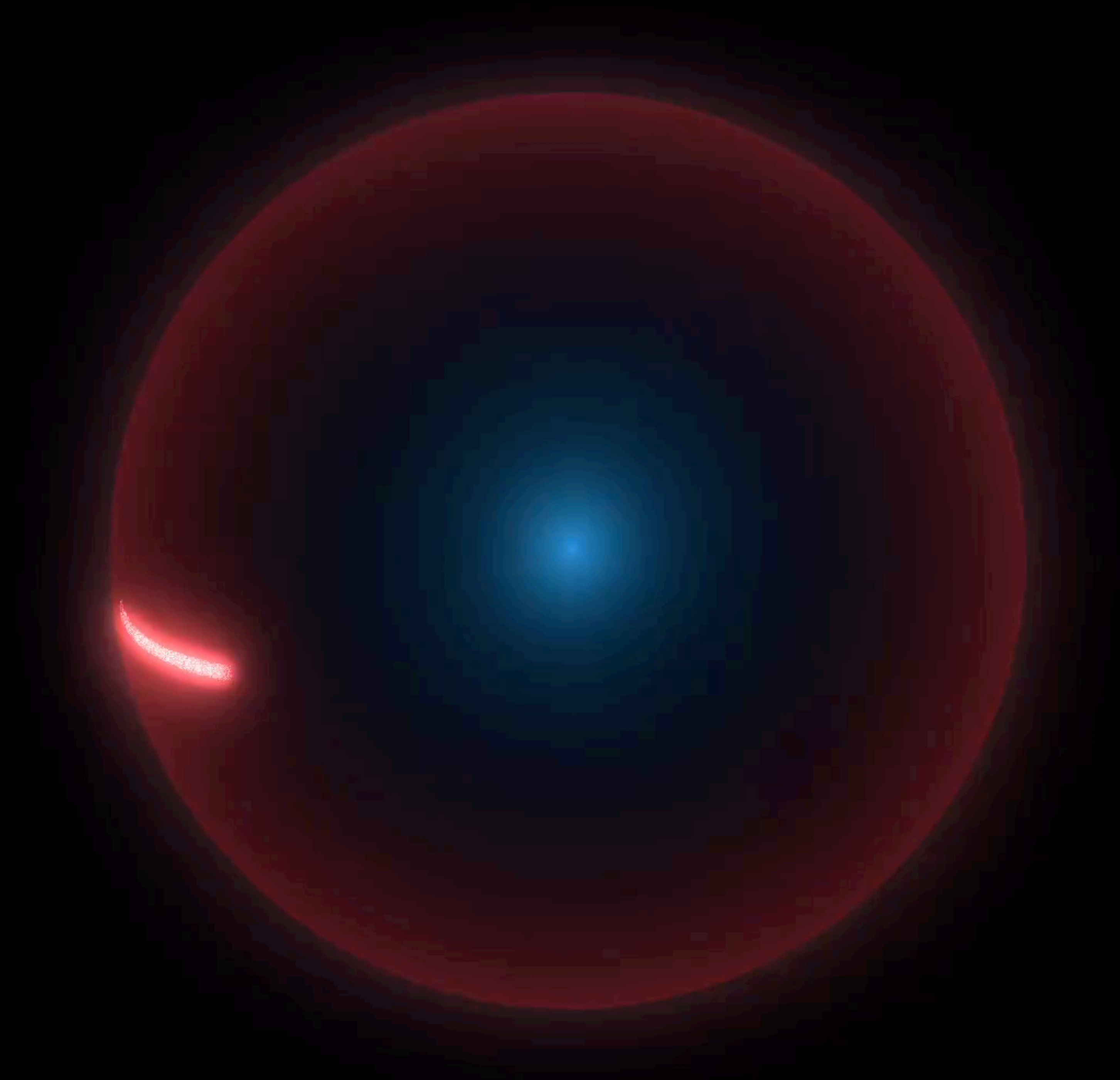
How does LIGO detect gravitational waves?



LIGO/Caltech

LIGO/Caltech

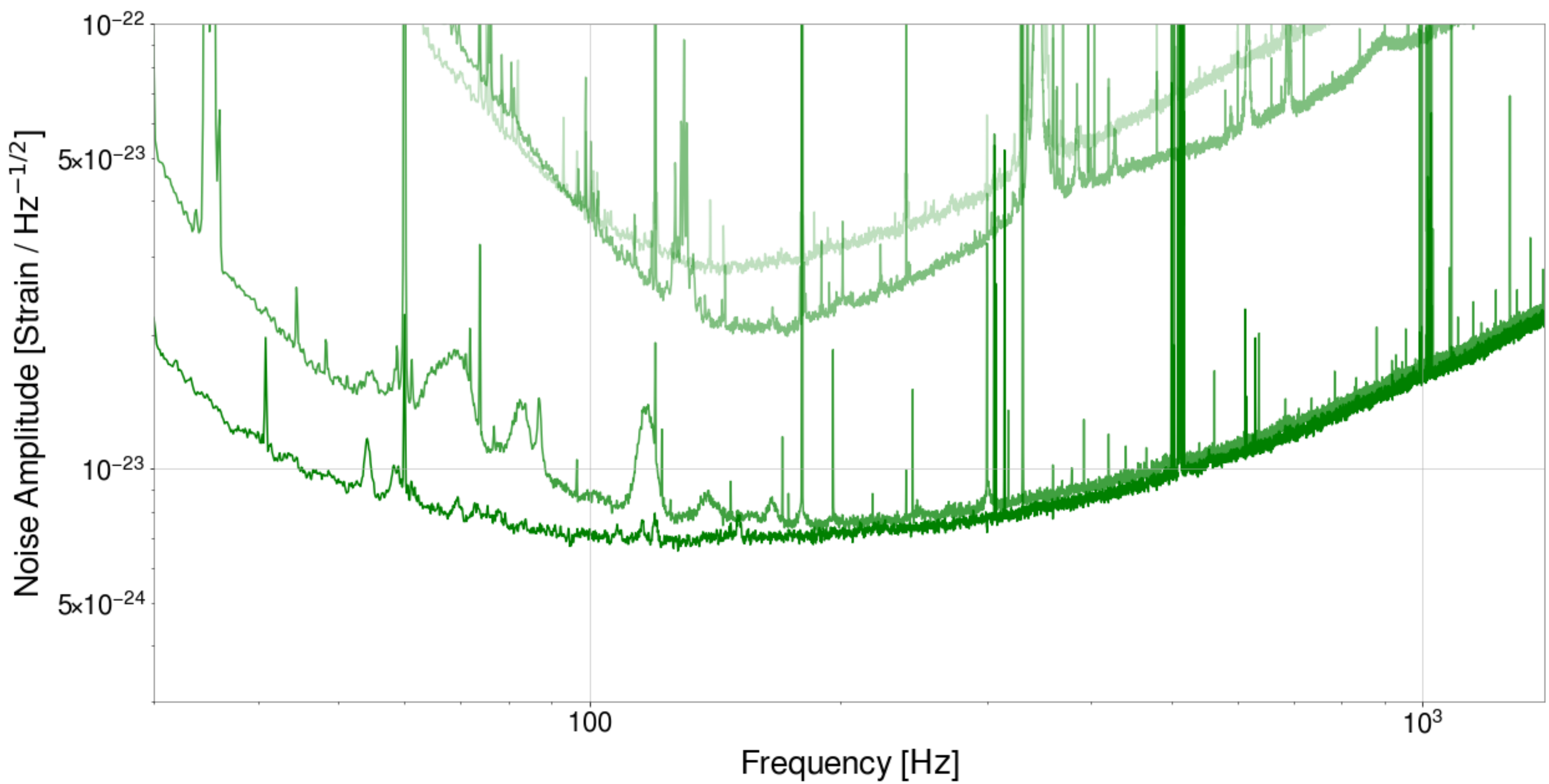
How sensitive is the LIGO experiment?



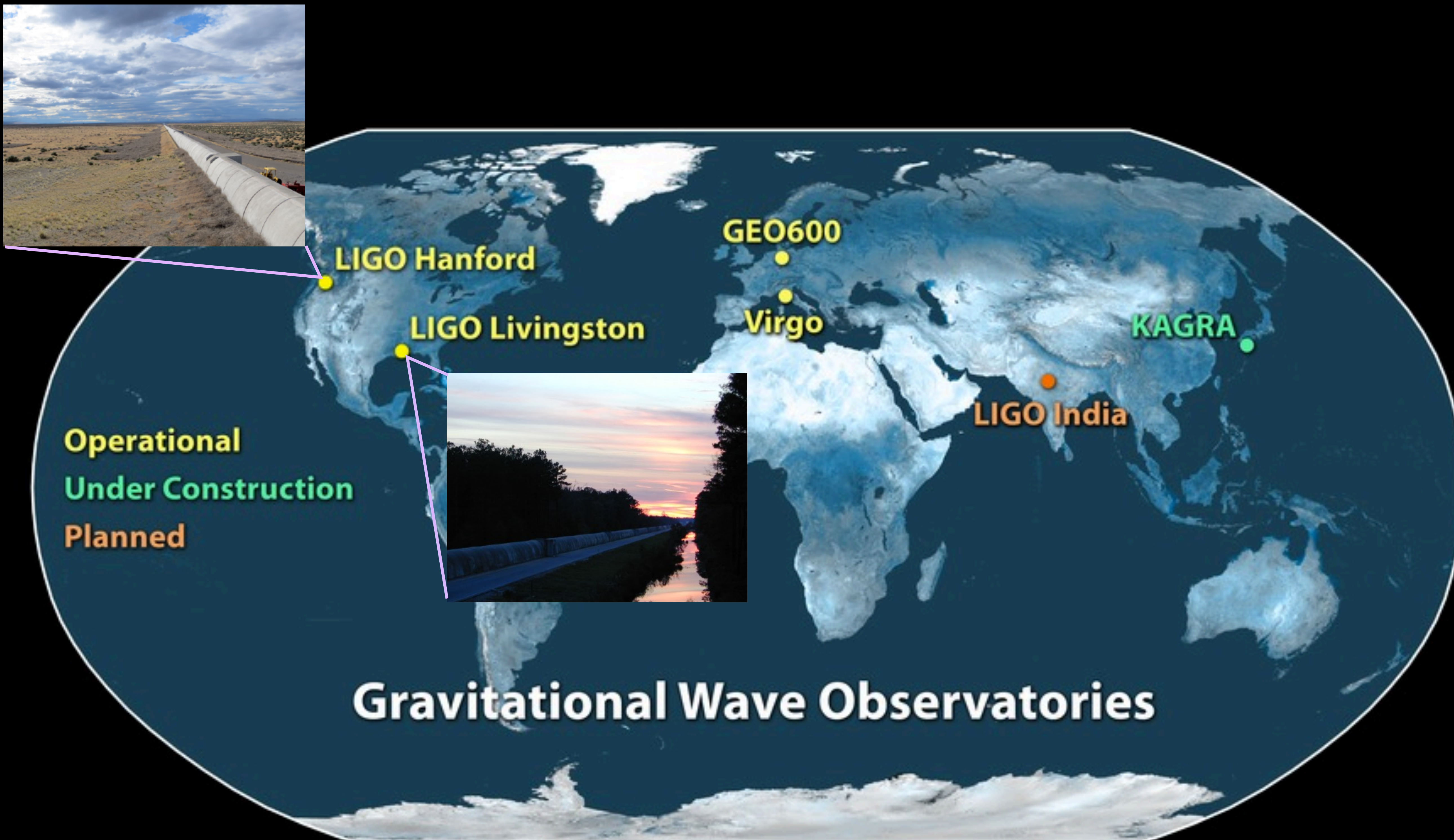
LIGO/Caltech

LIGO Sensitivity

Snapshots of LIGO (L1) Noise:
S5 (2007), S6 (2010), O1 (2016), O2 (2017)

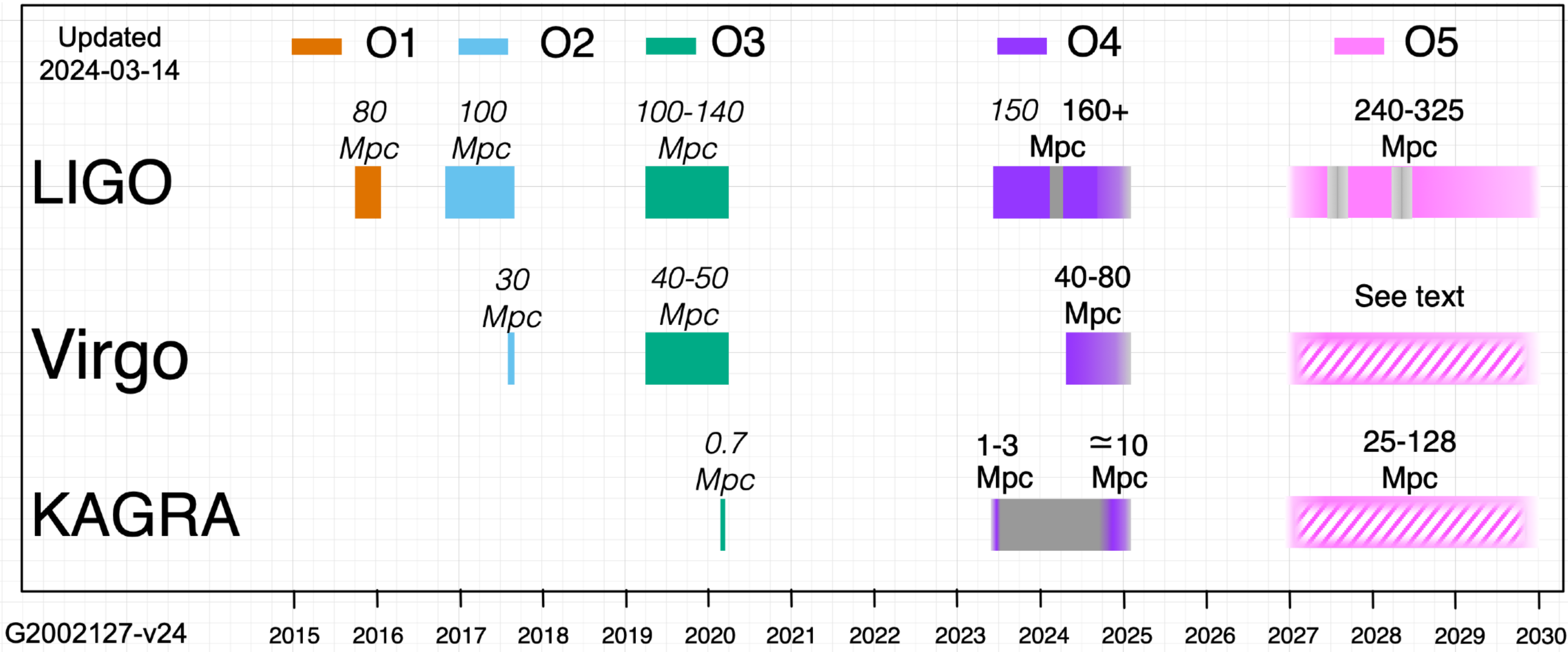


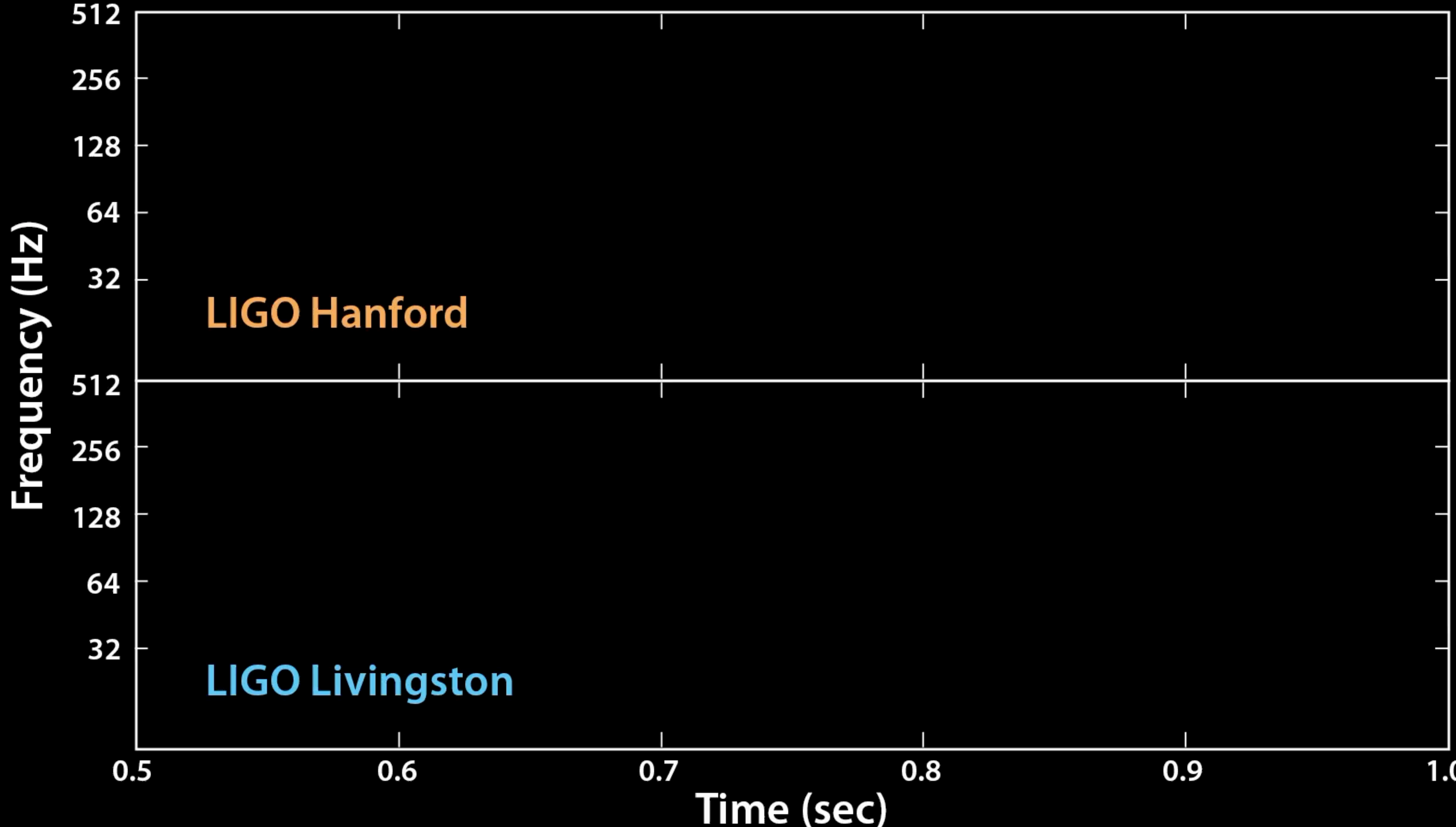
A Global Network



LIGO/Caltech

Observing Timeline

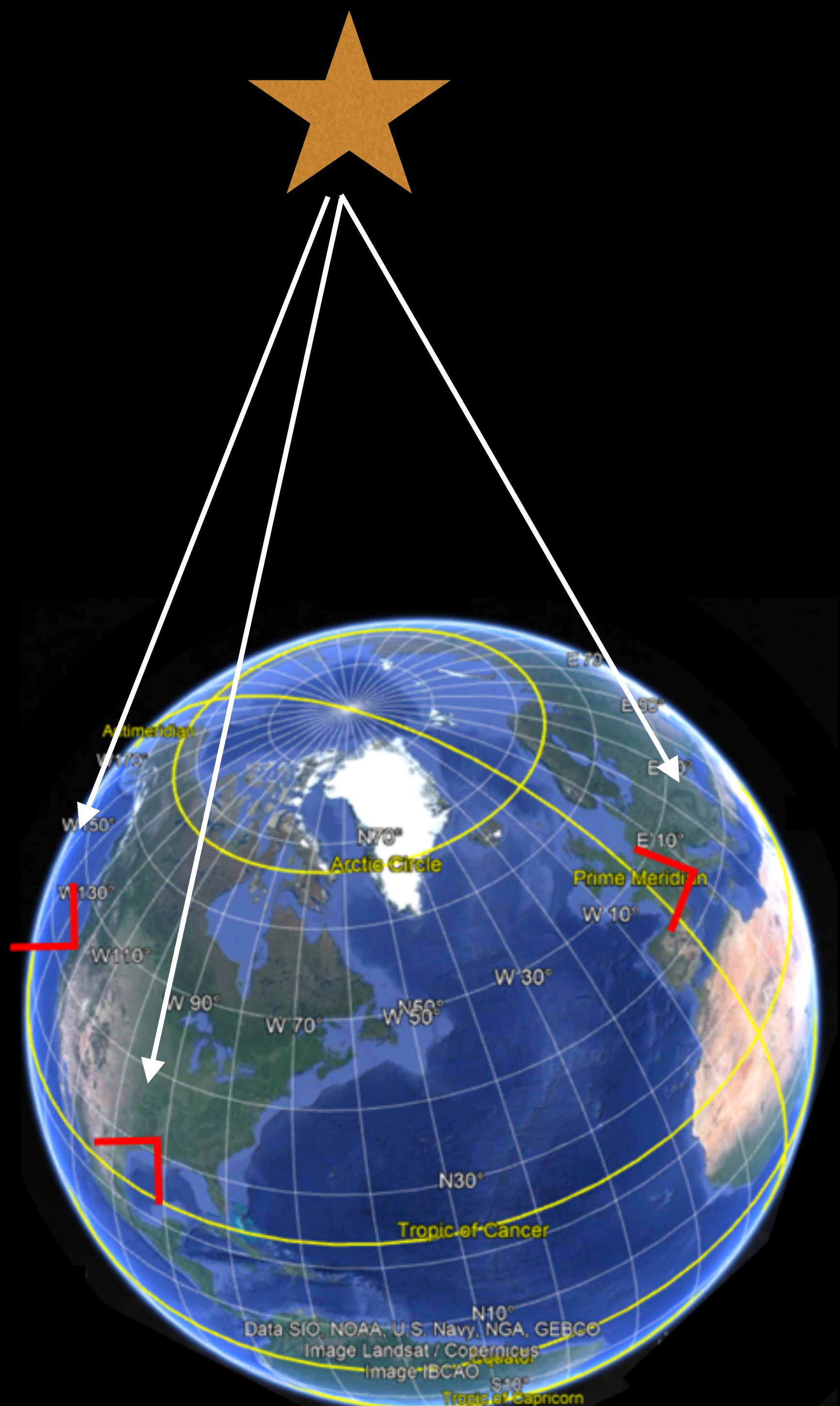


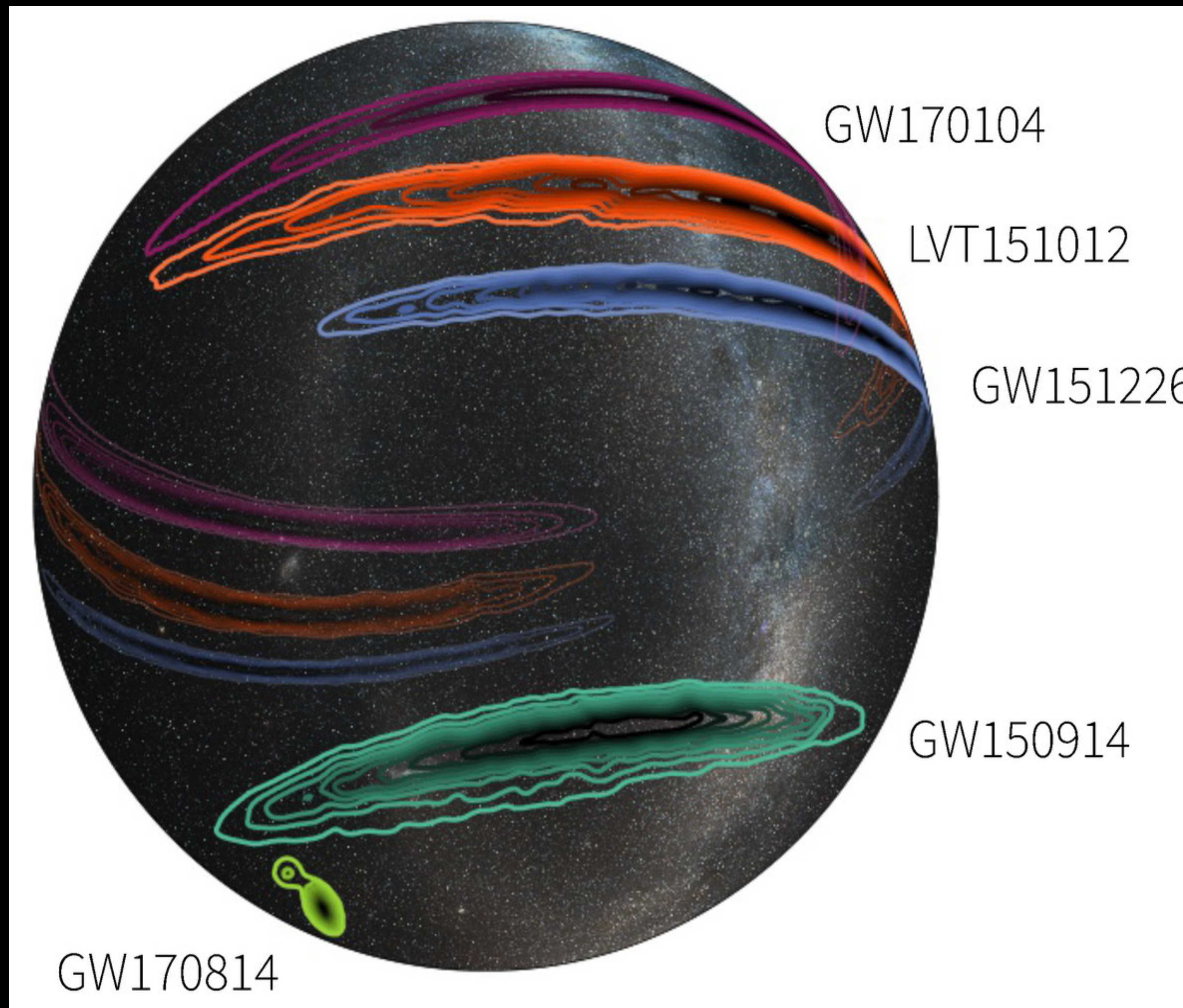


Caltech/MIT/LIGO Lab

First Detection, GW150914

A global network allows source localization





GraceDB — Gravitational-Wave Candidate Event Database

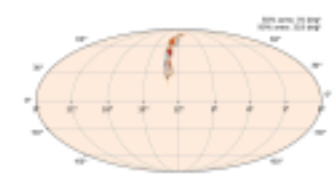
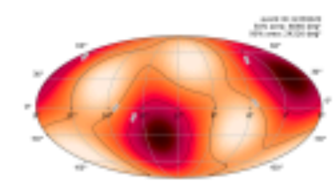
HOME	PUBLIC ALERTS	SEARCH	LATEST	DOCUMENTATION		LOGIN

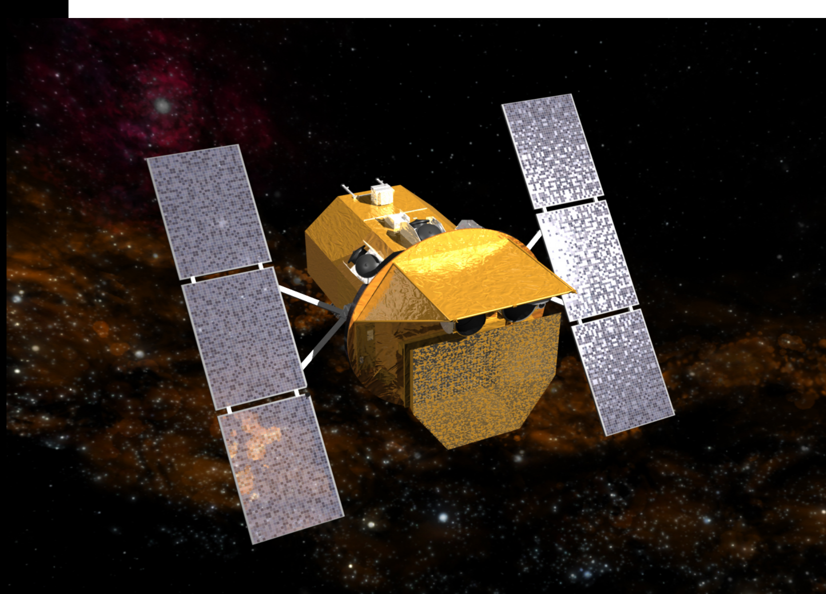
LIGO/Virgo O3 Public Alerts

Detection candidates: 29

Rapid Alerts for multi-messenger astronomy

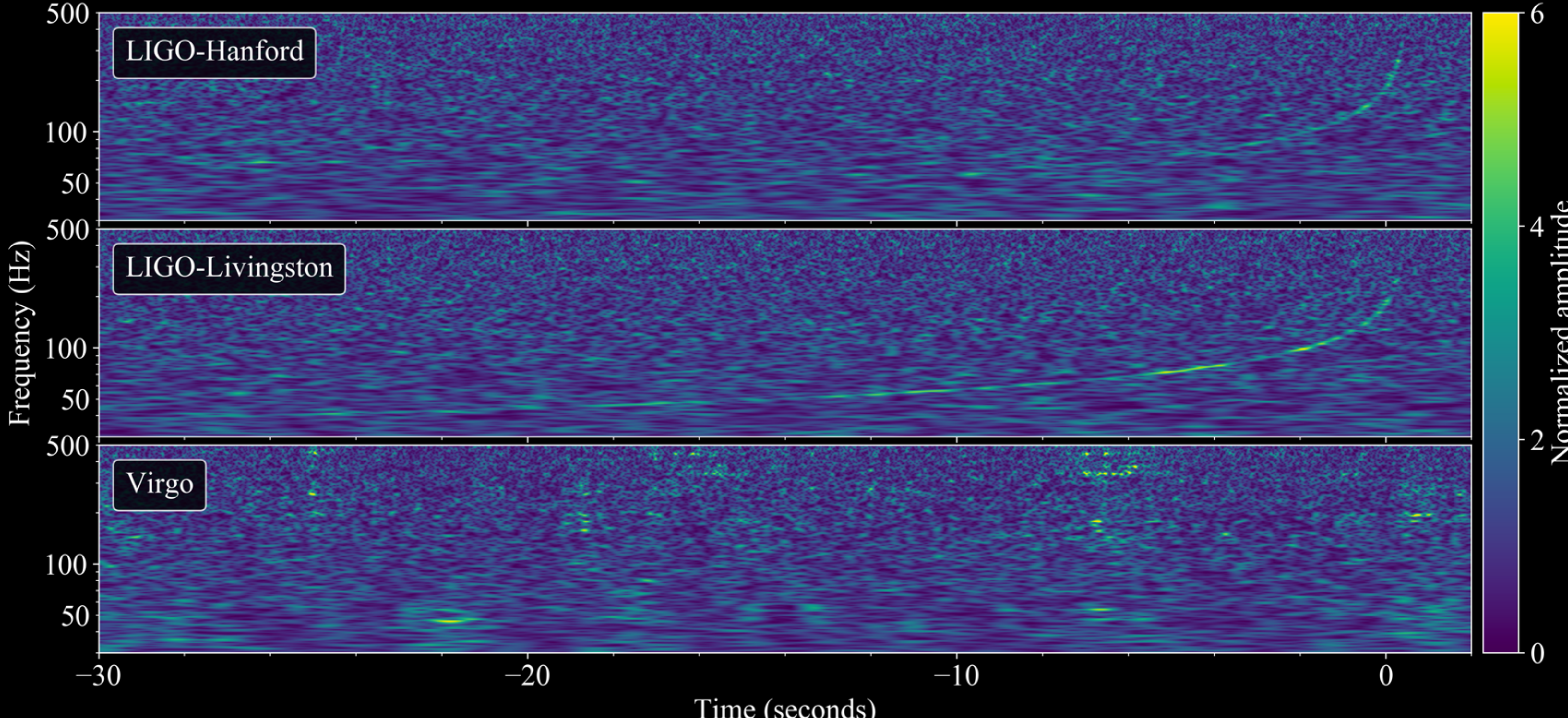
SORT: EVENT ID (A–Z) ▼

Event ID	Possible Source (Probability)	UTC	Location
S190915ak	BBH (99%)	Sept. 15, 2019 23:57:02 UTC	
S190910h	BNS (61%), Terrestrial (39%)	Sept. 10, 2019 08:29:58 UTC	



GW170817: gravitational waves from a binary neutron star merger

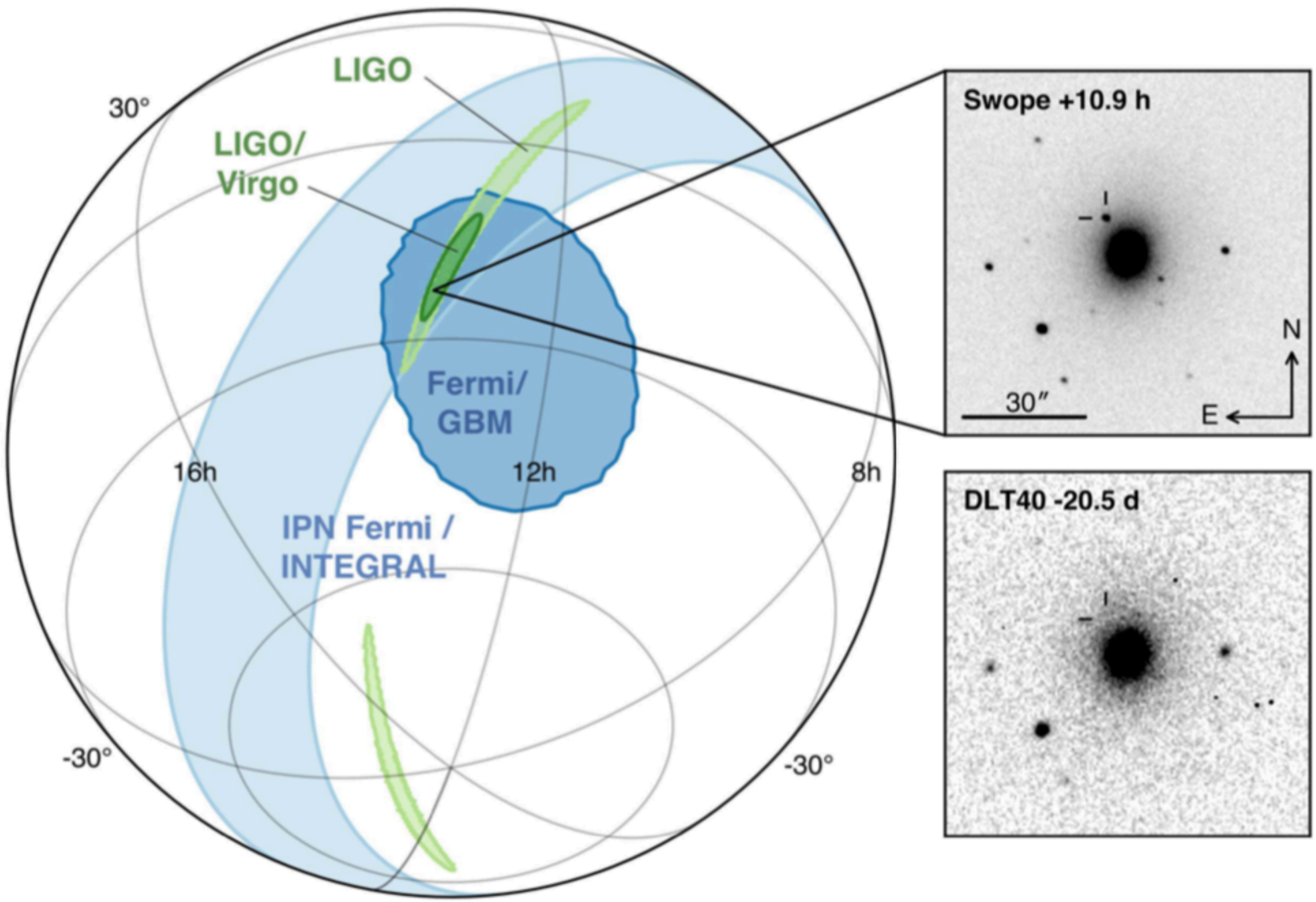
August 17, 2017



LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

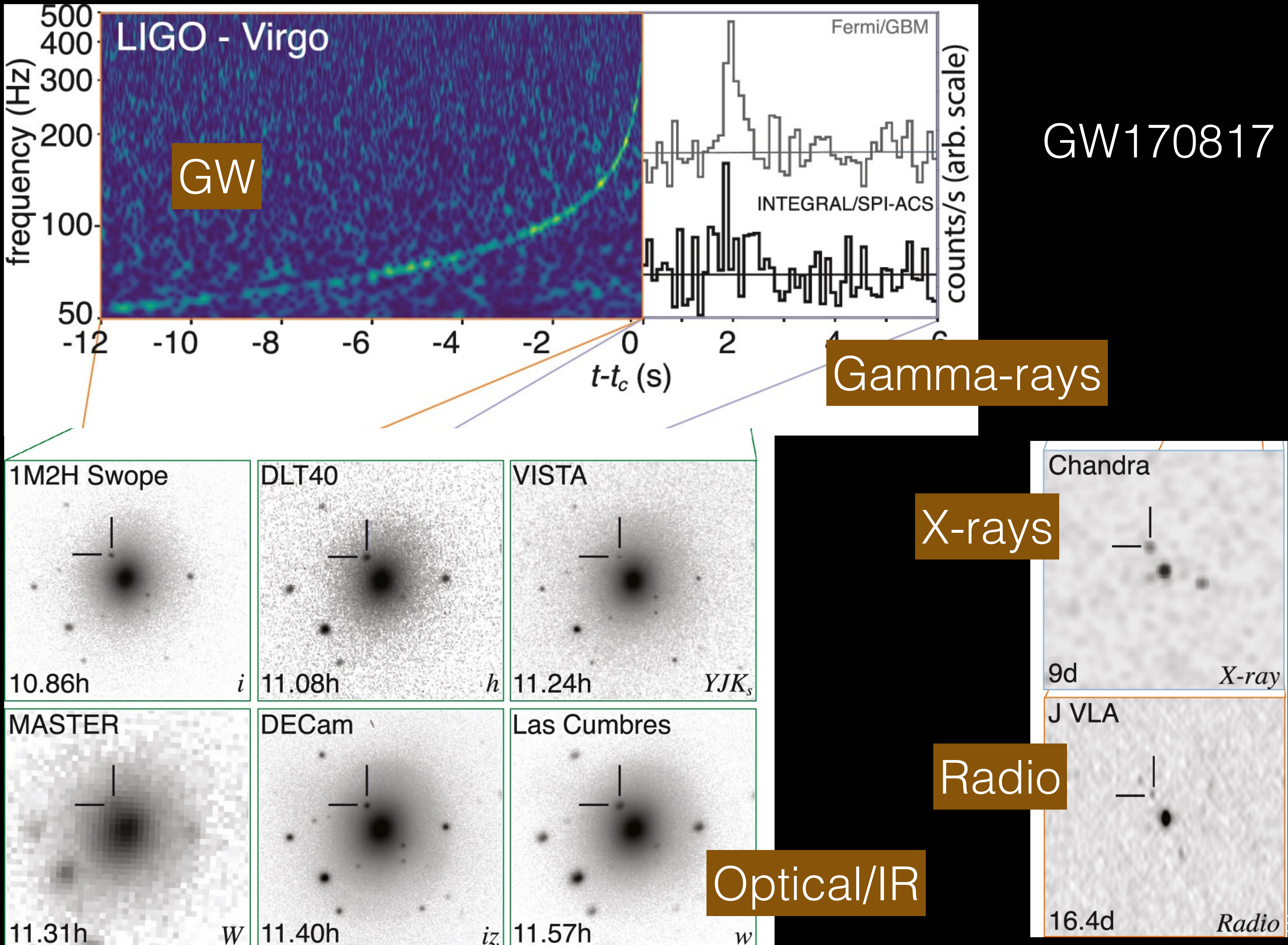
GW170817: Localization and optical counterpart

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

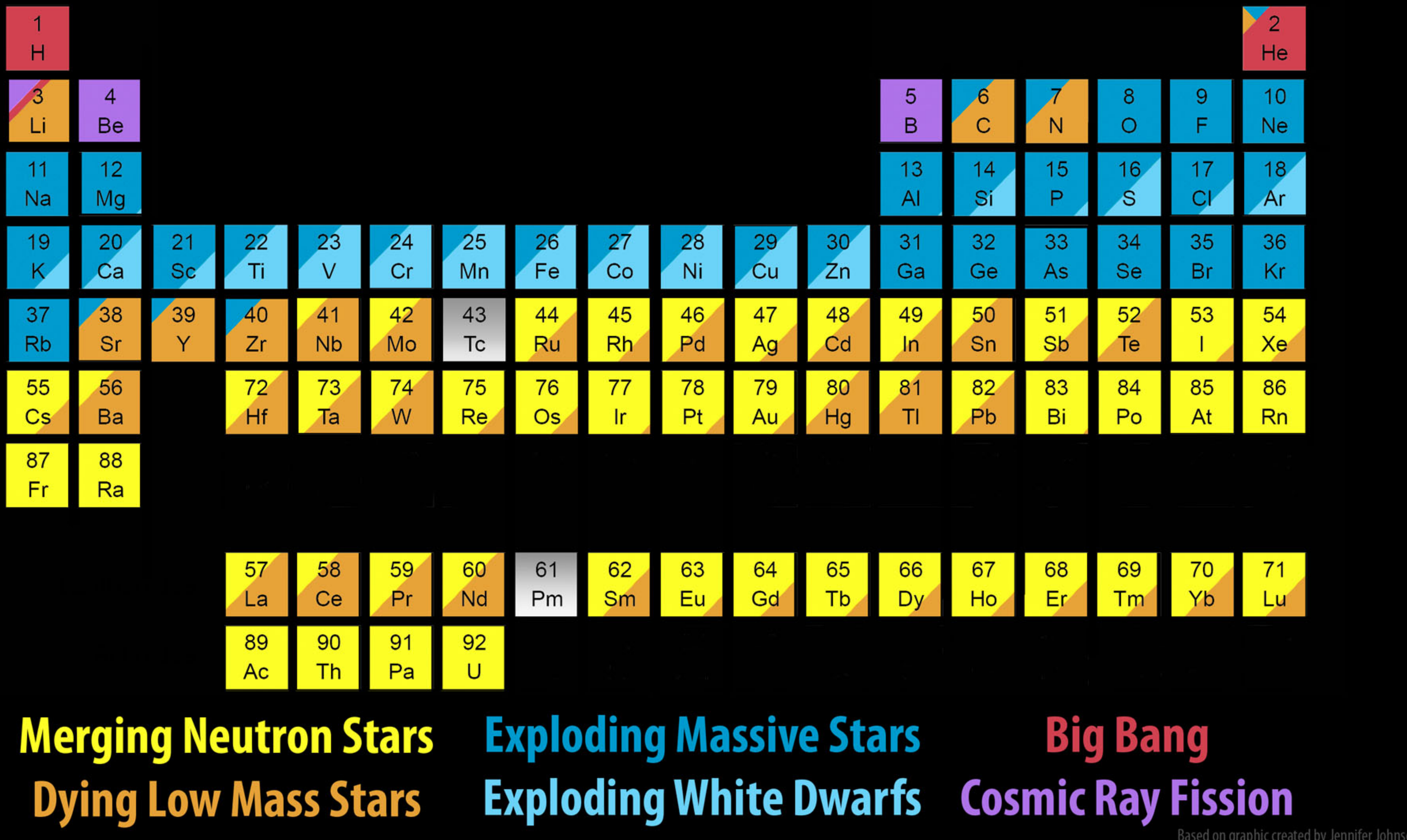


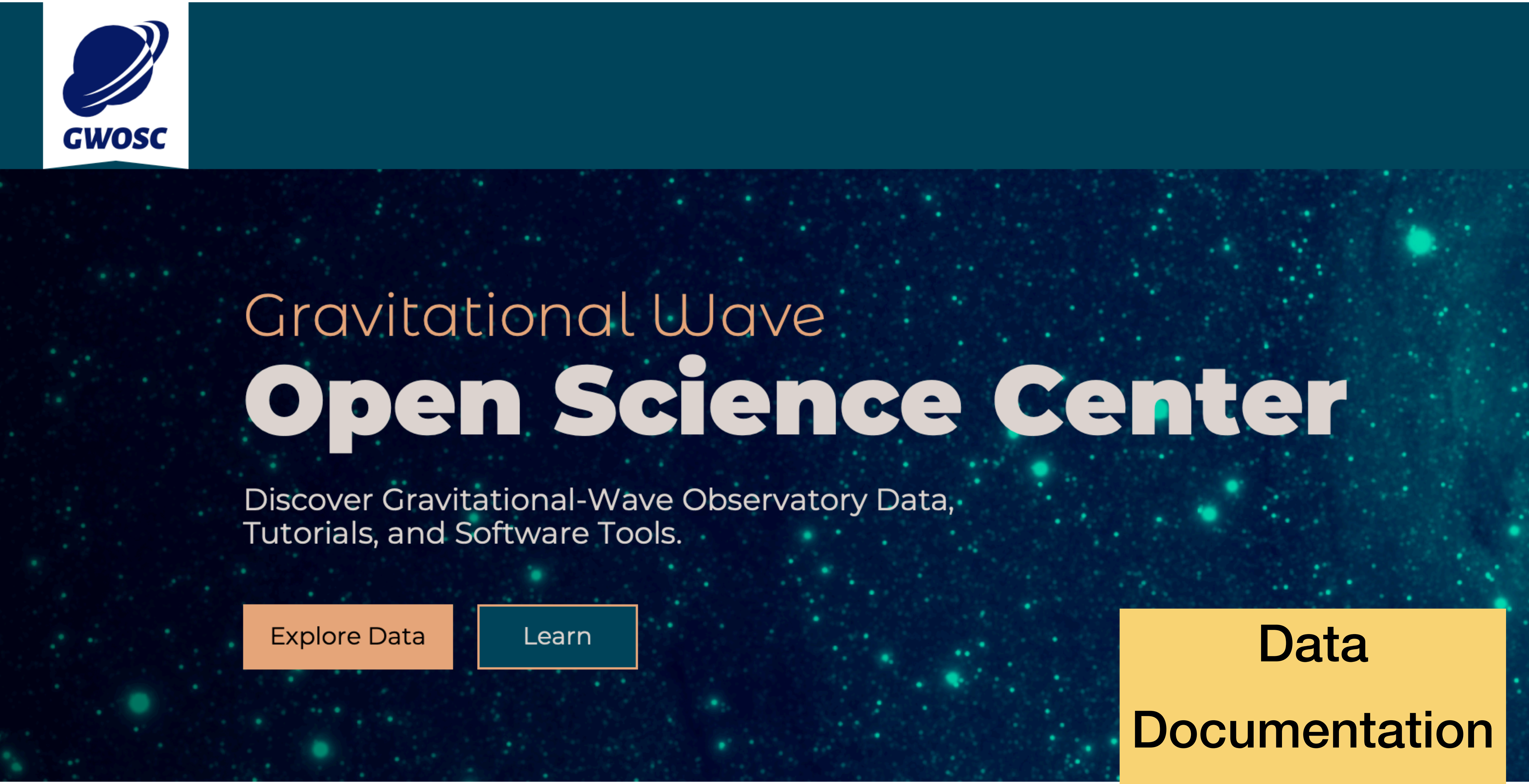
The Astrophysical Journal Letters, Volume 848, Number 2

GW170817



Binary neutron star mergers form heavy elements





Data

Documentation

Tutorials

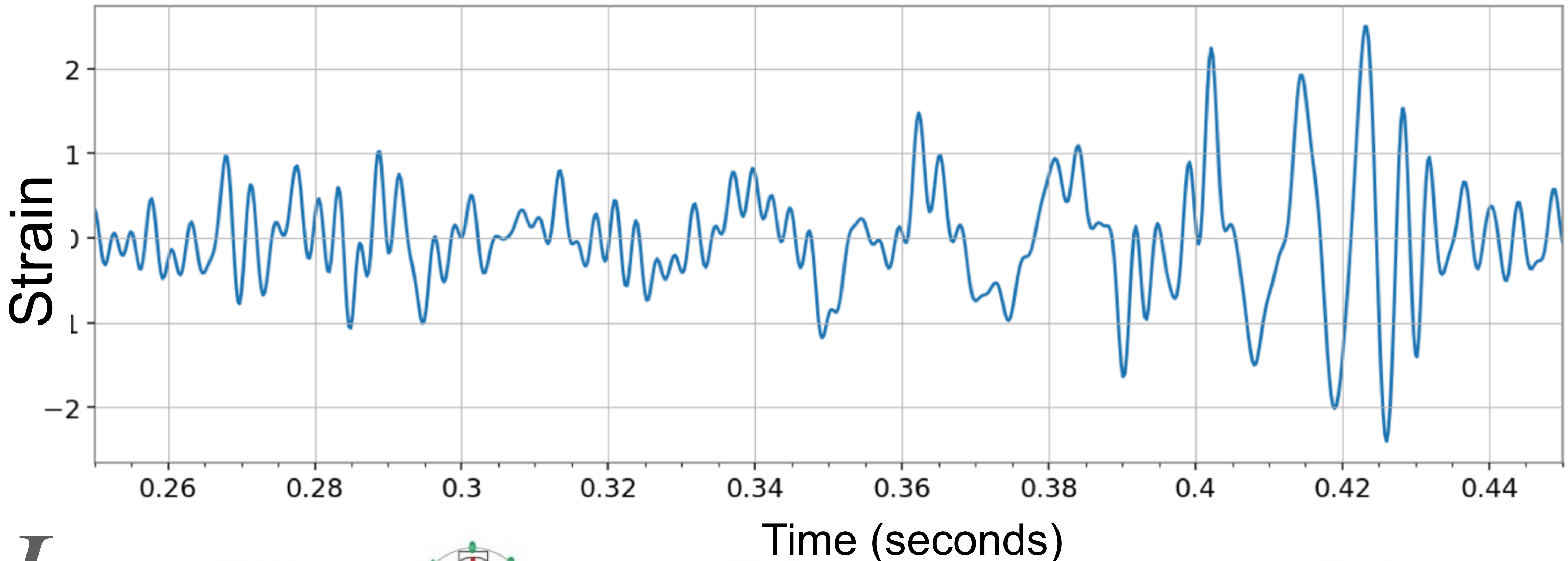
Software

Segment Lists

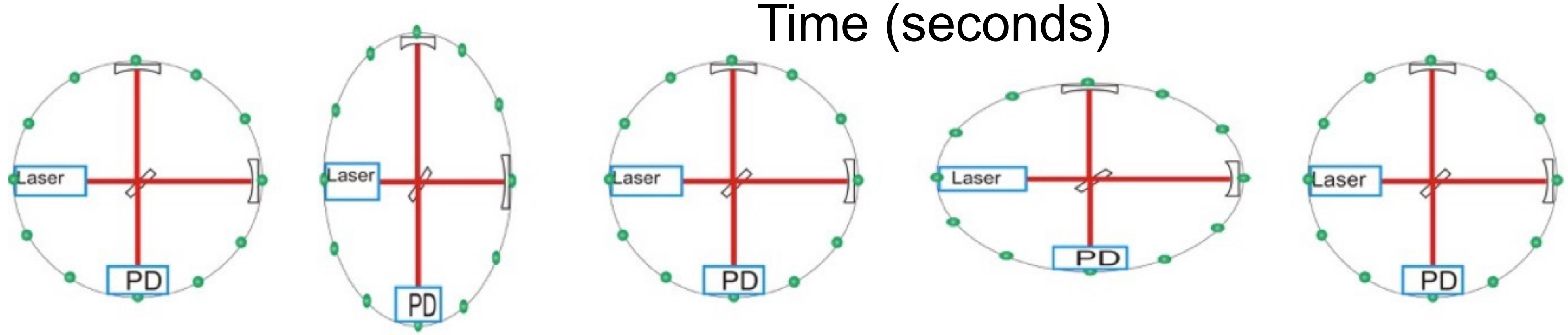
Web Apps

gwosc.org

Time Domain Strain Data

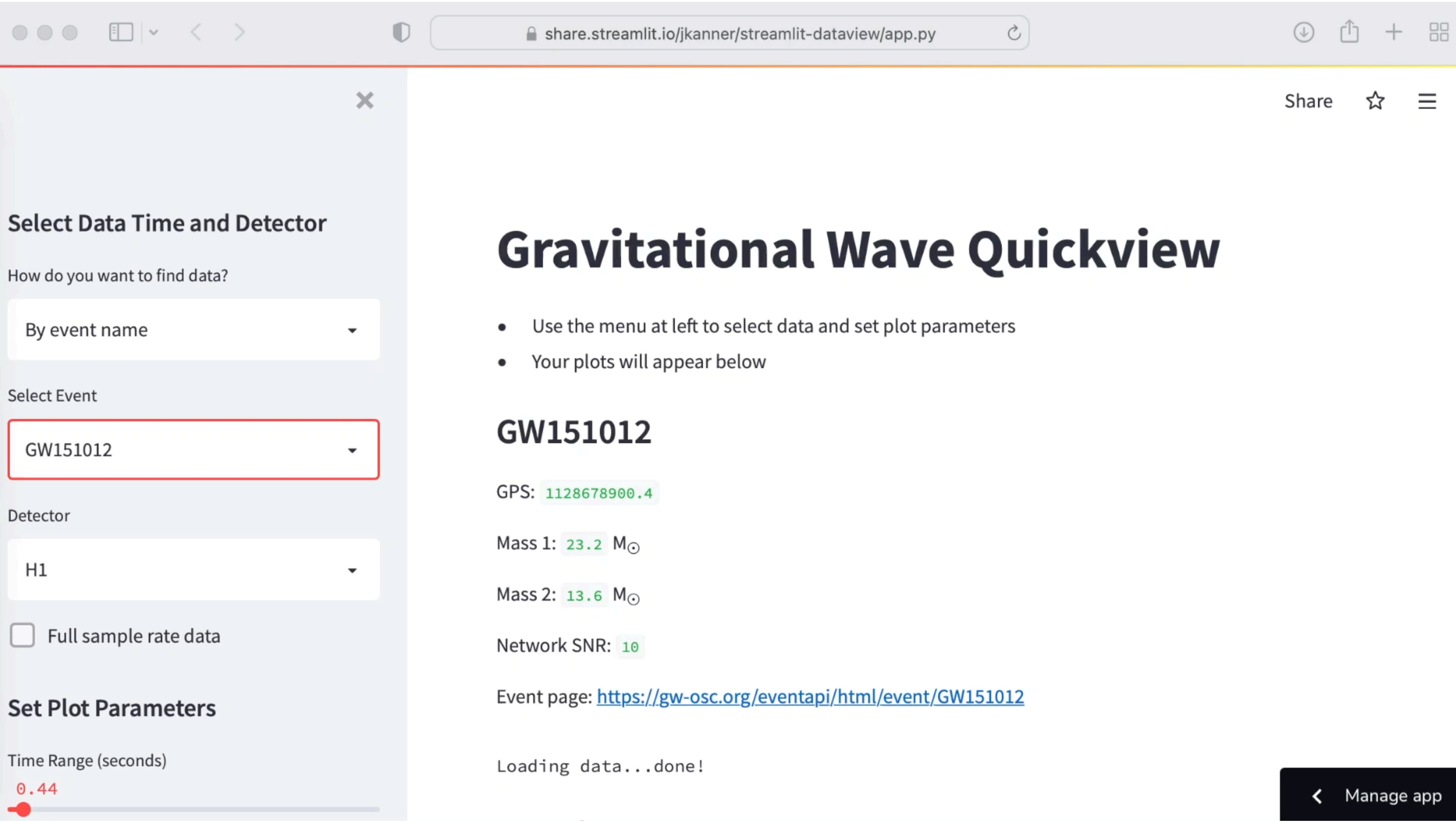


$$\frac{\Delta L}{L}$$



Explore Strain: GW Quickview App

https://gw-quickview.streamlit.app/


share.streamlit.io/jkanner/streamlit-dataview/app.py
Share
Select Data Time and Detector
How do you want to find data?
By event name
Select Event
GW151012
Detector
H1
Full sample rate data
Set Plot Parameters
Time Range (seconds)
0.44
Gravitational Wave Quickview
Use the menu at left to select data and set plot parameters
Your plots will appear below
GW151012
GPS: 1128678900.4
Mass 1: 23.2 M☉
Mass 2: 13.6 M☉
Network SNR: 10
Event page: https://gw-osc.org/eventapi/html/event/GW151012
Loading data...done!
Manage app

Event Catalogs

Event Portal

GW200129_065458

Documentation

Release: GWTC-3-confident

Event UID: GW200129_065458-v1

Names: GW200129_065458

GPS: 1264316116.4

UTC Time: 2020-01-29 06:54

GraceDB: S200129m

GCN: Notices · Circulars

Timeline: Query for segments

DOI: https://doi.org/10.7935/b024-1886

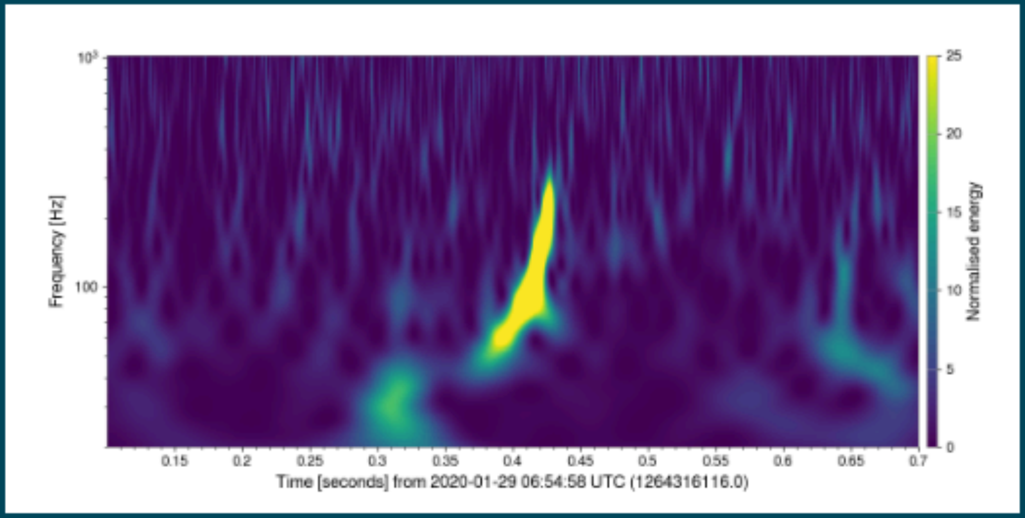
Data sourced from frame channels.

FrameChannels: [H1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, L1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, V1:Hrec_hoft_16384Hz]

Data sourced from frame types:

FrameTypes: [H1_HOFT_CLEAN_SUB60HZ_C01, L1_HOFT_CLEAN_SUB60HZ_C01, V1Online]

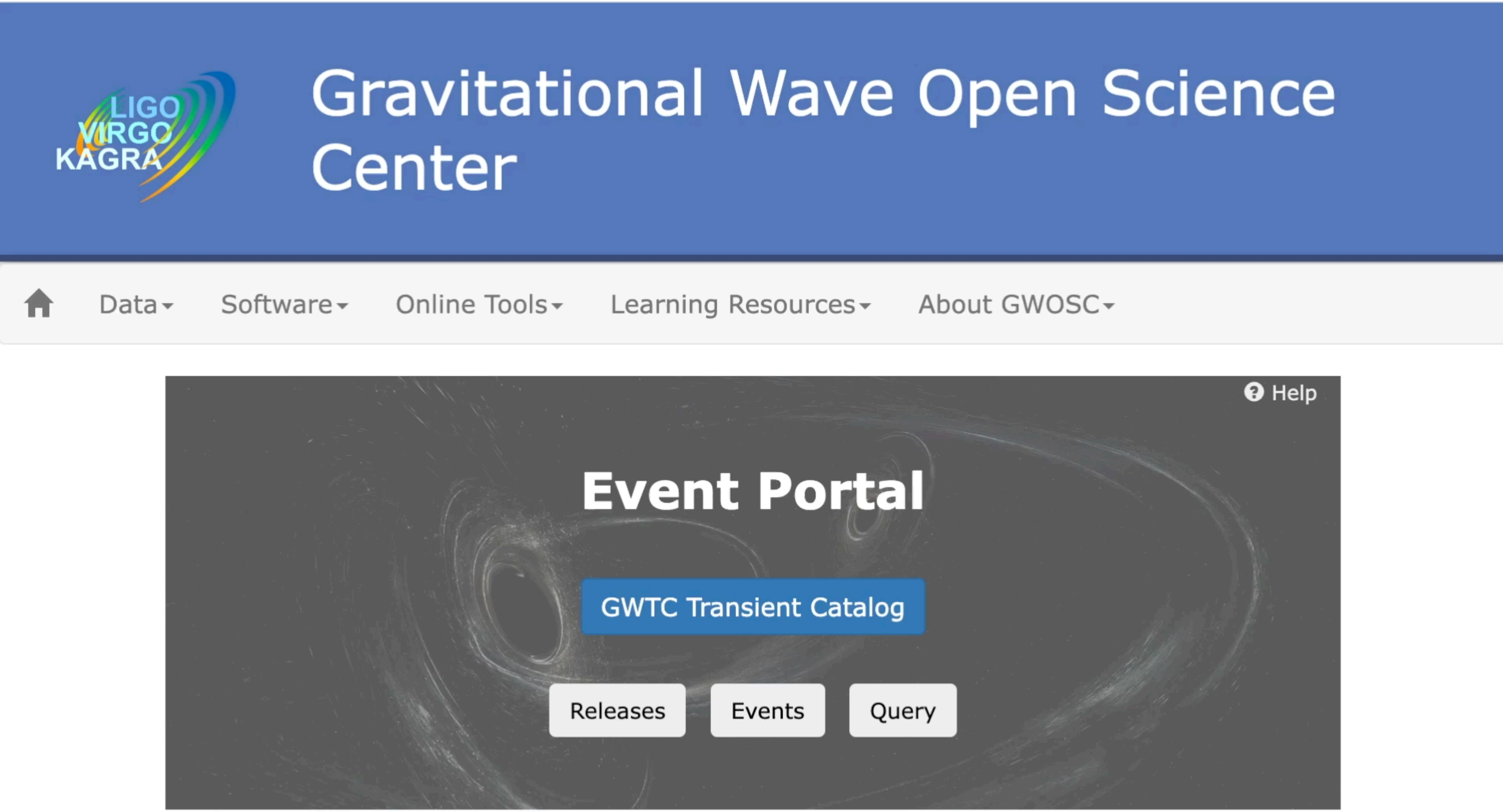
H1 strain



32sec · 16KHz:	GWF	HDF	TXT
32sec · 4KHz:	GWF	HDF	TXT
4096sec · 16KHz:	GWF	HDF	TXT
4096sec · 4KHz:	GWF	HDF	TXT

GWOSC.ORG

93 events & counting



Download LIGO/Virgo data through:

Point and click
Scriptable API
CVMFS

	Universal Time (ISO8601)		GPS Time	
Start Time	2016-11-30T16:00:00	⇔	1164556817	OK
End Time	2017-08-25T22:00:00	⇔	1187733618	OK

Timeline	UTC	Mbytes	HDF5	Frame	Percent
1164599296	2016-12-01T03:47:59	327 MB	HDF5	Frame	63
1164603392	2016-12-01T04:56:15	515 MB	HDF5	Frame	100
1164607488	2016-12-01T06:04:31	333 MB	HDF5	Frame	64
1164611584	2016-12-01T07:12:47	336 MB	HDF5	Frame	65

Open Data Workshops

[Link to slides, tutorial]

Duncan McLeod, Introduction to GWpy

[Link to slides, tutorial]

Ed Porter, Basics of compact binary searches

[Link to slides, tutorial]

Learn GW data analysis
Attend in person or online course
Lecture videos + software tutorials

gwosc.org/workshops

Learning Path | Signal Processing Tutorial · Streamlit | GW Quickview · Streamlit

Share

Select Data Time and Detector

How do you want to find data?

By event name

Select Event

GW170608

Detector

H1

☐ Full sample rate data

Set Plot Parameters

Time Range (seconds)

1.22

0.10 8.00

Whitened and band-passed data

☑ Whiten?

Gravitational Wave Quickview

- Use the menu at left to select data and set plot parameters
- Your plots will appear below

GW170608

GPS: `1180922494.5`

Mass 1: `11.0` $M_\odot$

Mass 2: `7.6` $M_\odot$

Network SNR: `15`

Event page: https://gwosc.org/eventapi/html/event/GW170608

```
Loading data...done!
```

Raw data

Manage app

Summary

- **Gravitational waves** are providing insights across many fields, including:
  - Hubble constant
  - Neutron star equation of state
  - Heavy element production
  - Jet structure
  - Compact object populations
  - and more ….

- LIGO and Virgo are part of a global, rapidly developing network of GW observatories

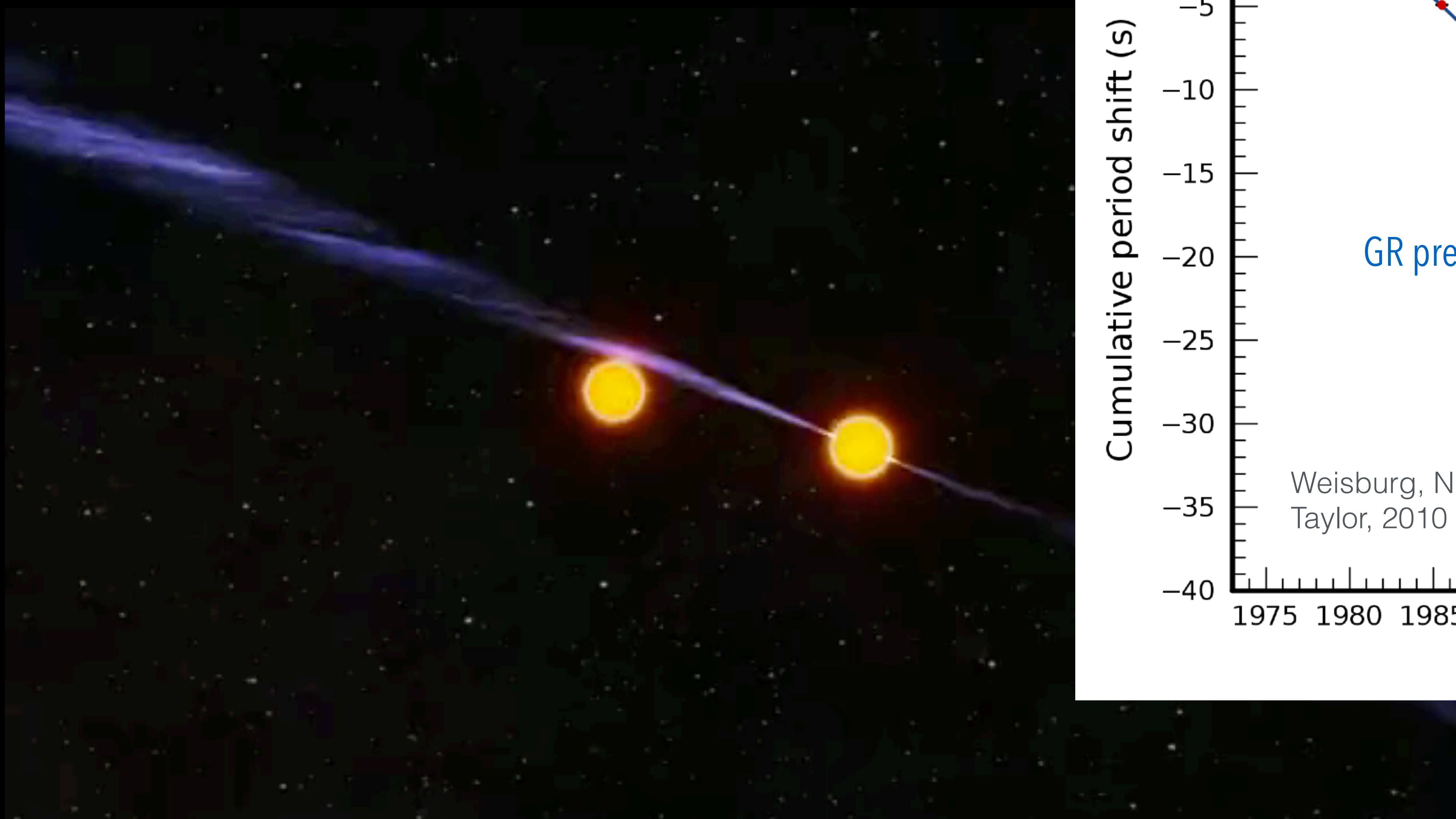
- Get started at **gwosc.org**

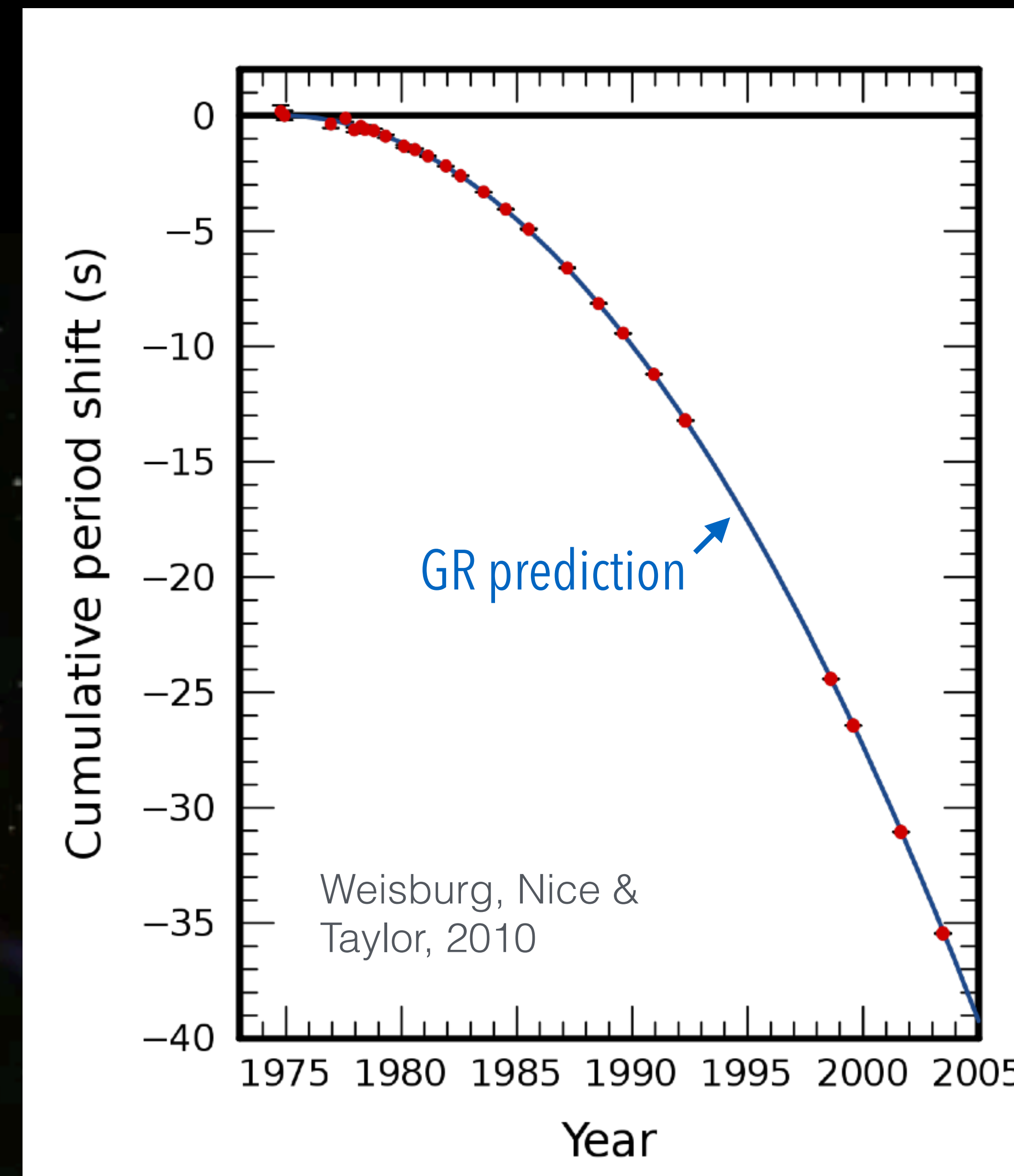
- Many more discoveries to come!

Thank you!

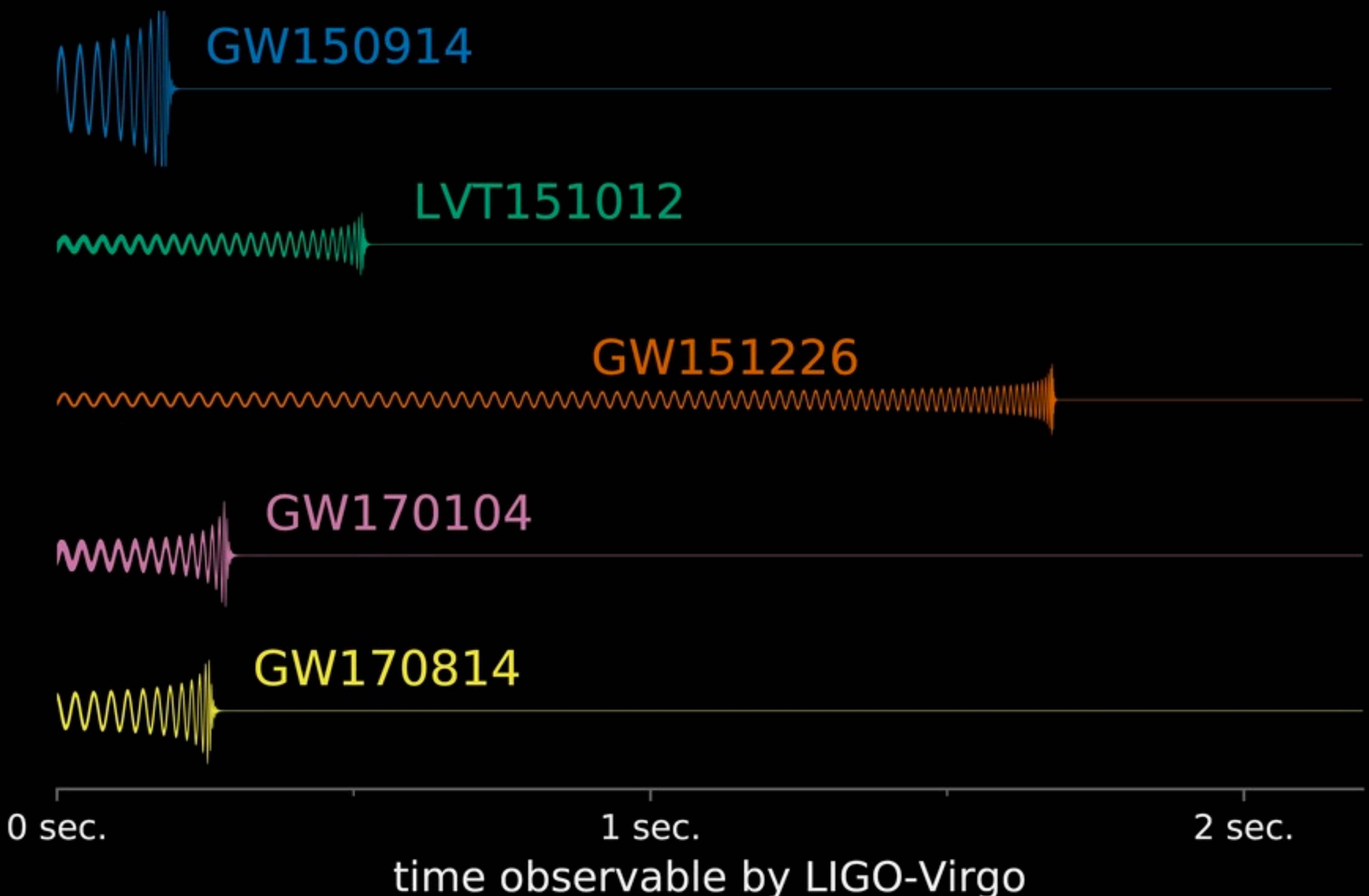
Indirect evidence of gravitational waves

Hulse-Taylor Binary Pulsar
PSR B1913+16



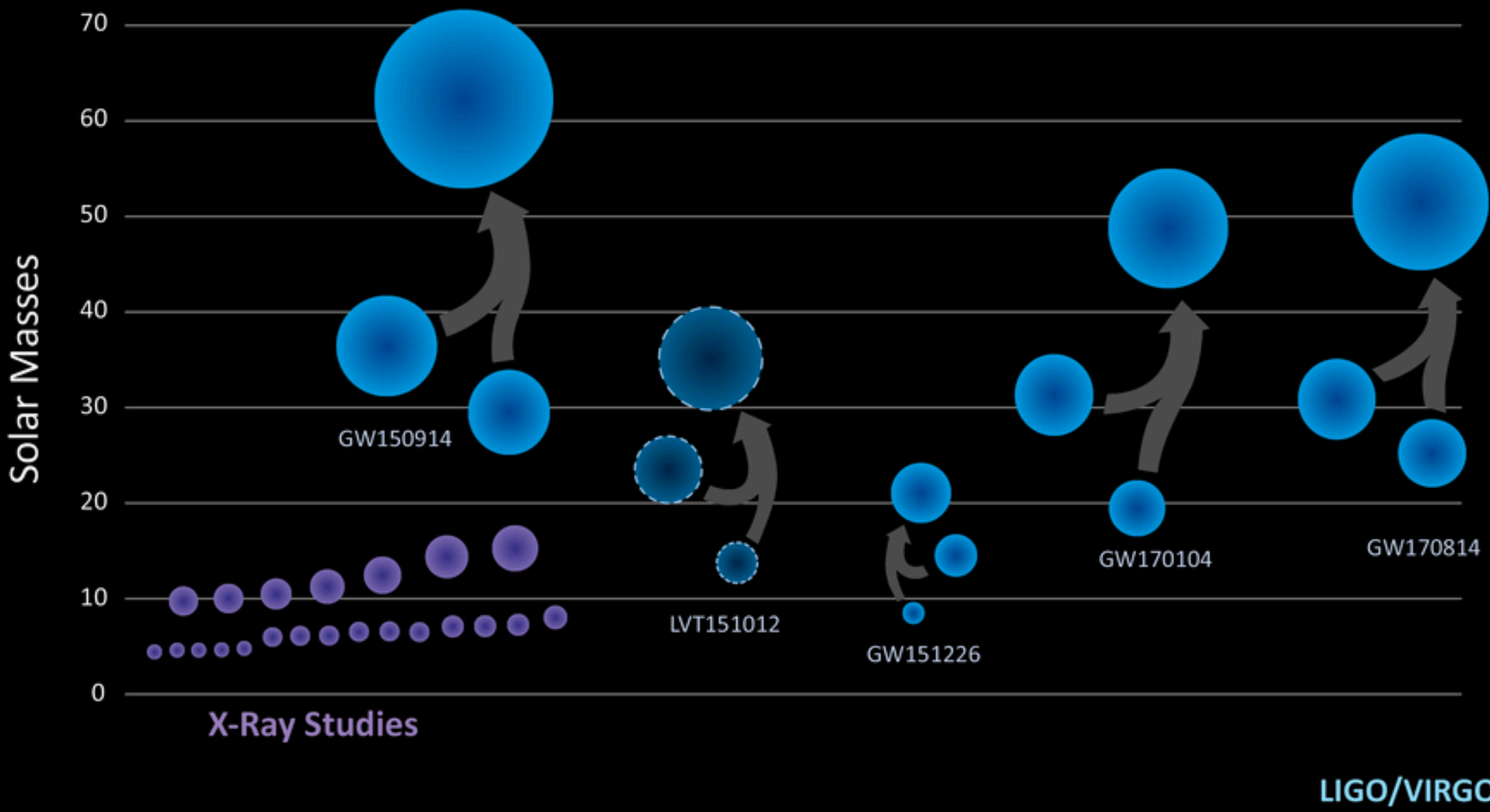


Observed black hole mergers to date



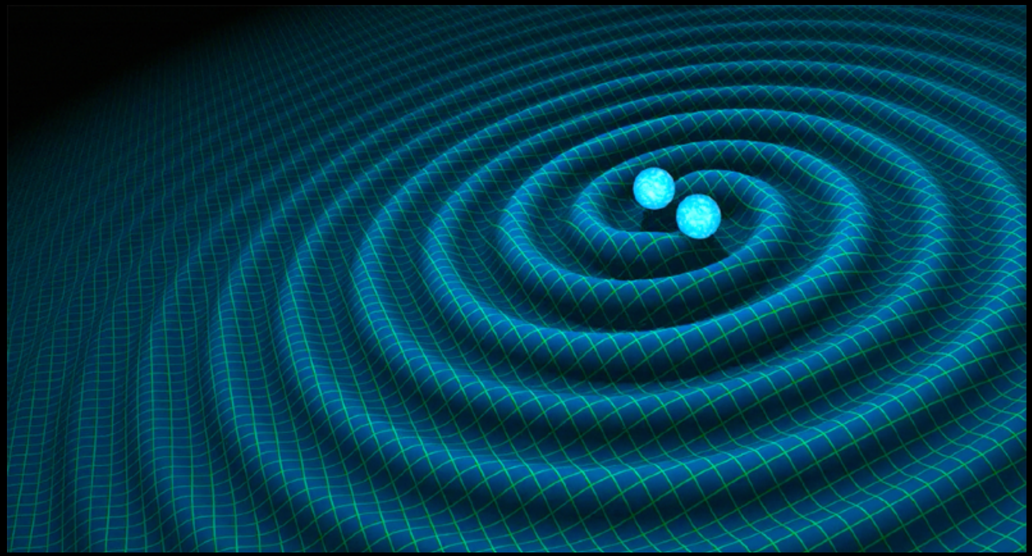
LIGO/Caltech/MIT/LSC

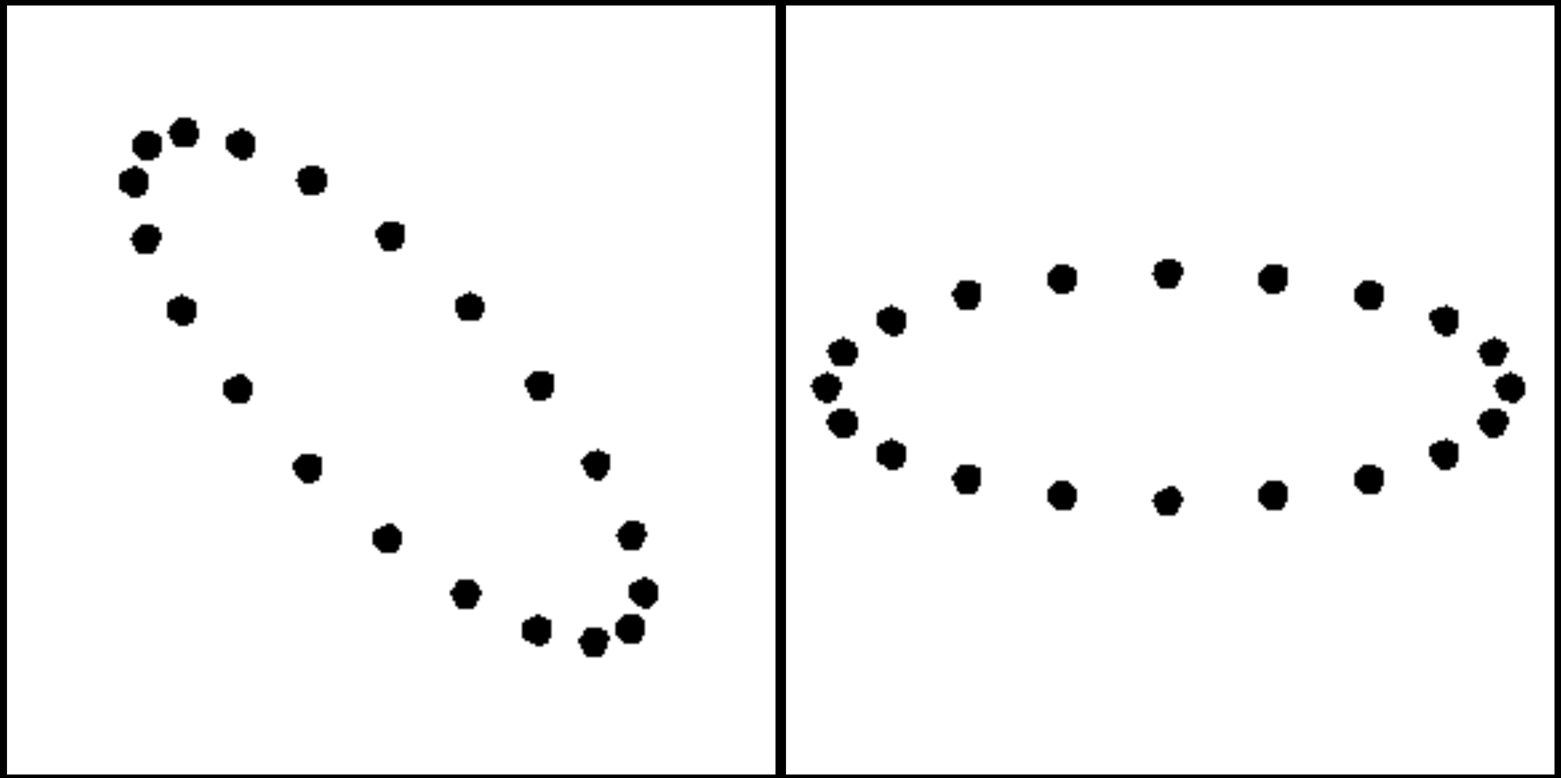
Black Holes of Known Mass



LIGO/Caltech

Gravitational Waves Stretch Spacetime





Introductions

- Jonah Kanner
- Senior scientist with LIGO Laboratory, Caltech
  - Director of the Gravitational Wave Open Science Center
- I have 2 jobs:
  - I write software to look for gravitational waves
  - I help other people write software to look for gravitational waves
- contact: jonah@caltech.edu

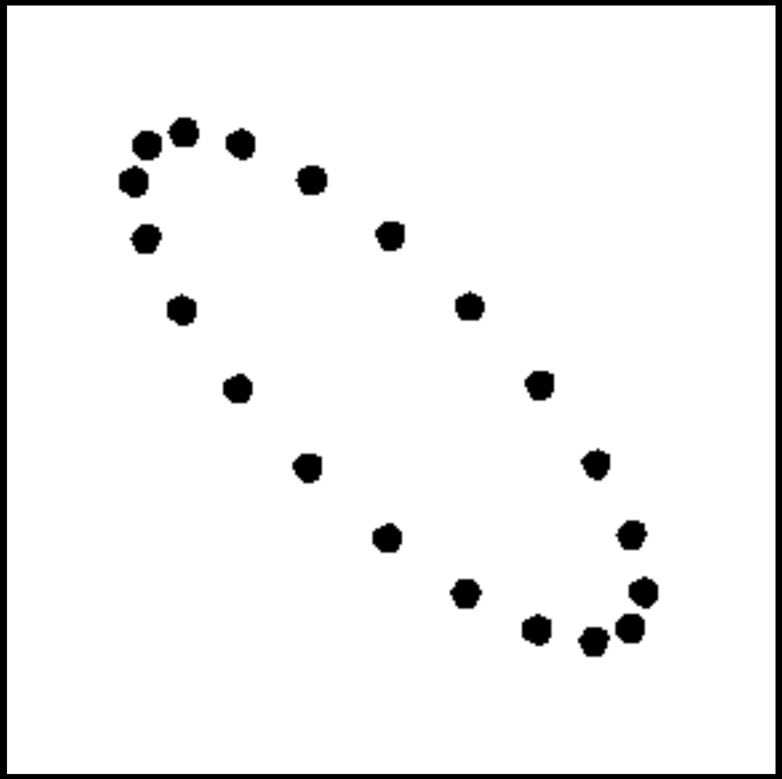
Career path:

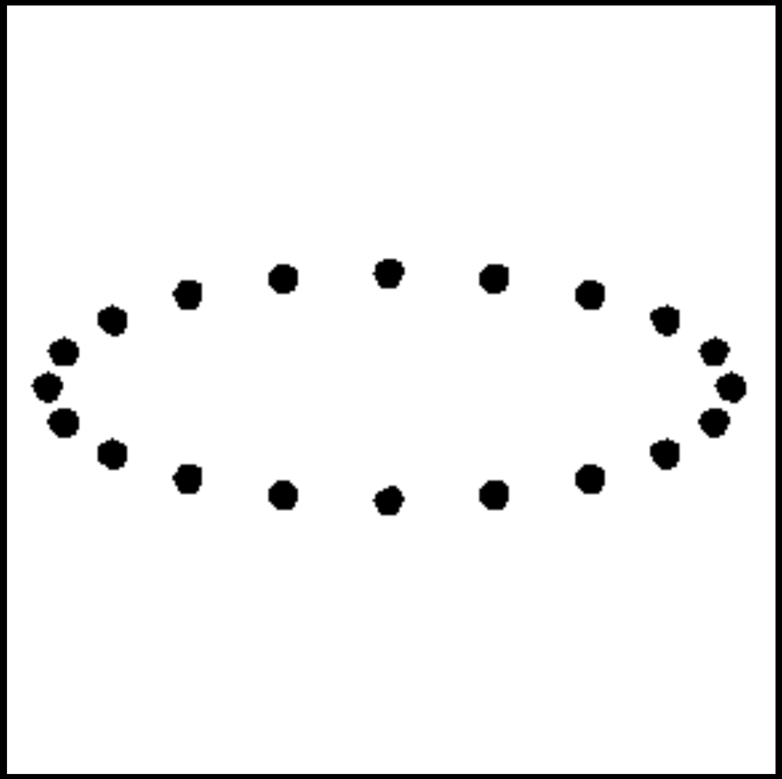
Bachelors in physics+math, then PhD in physics (UMD)

1.5 year “post-doc” at NASA Goddard

Gravitational wave propagation

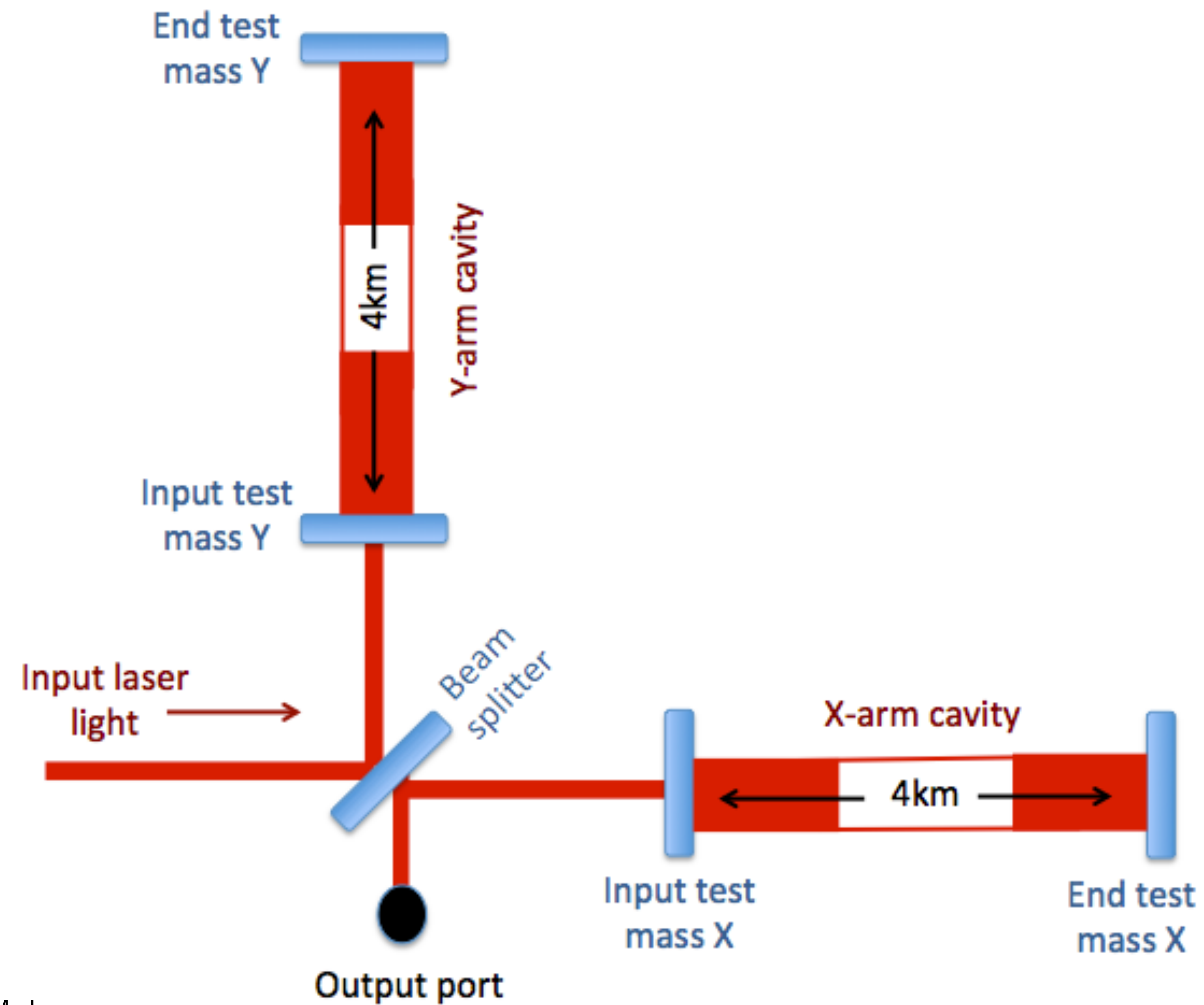
Spacetime strain h(t) measured as $\frac{\Delta L}{L}$



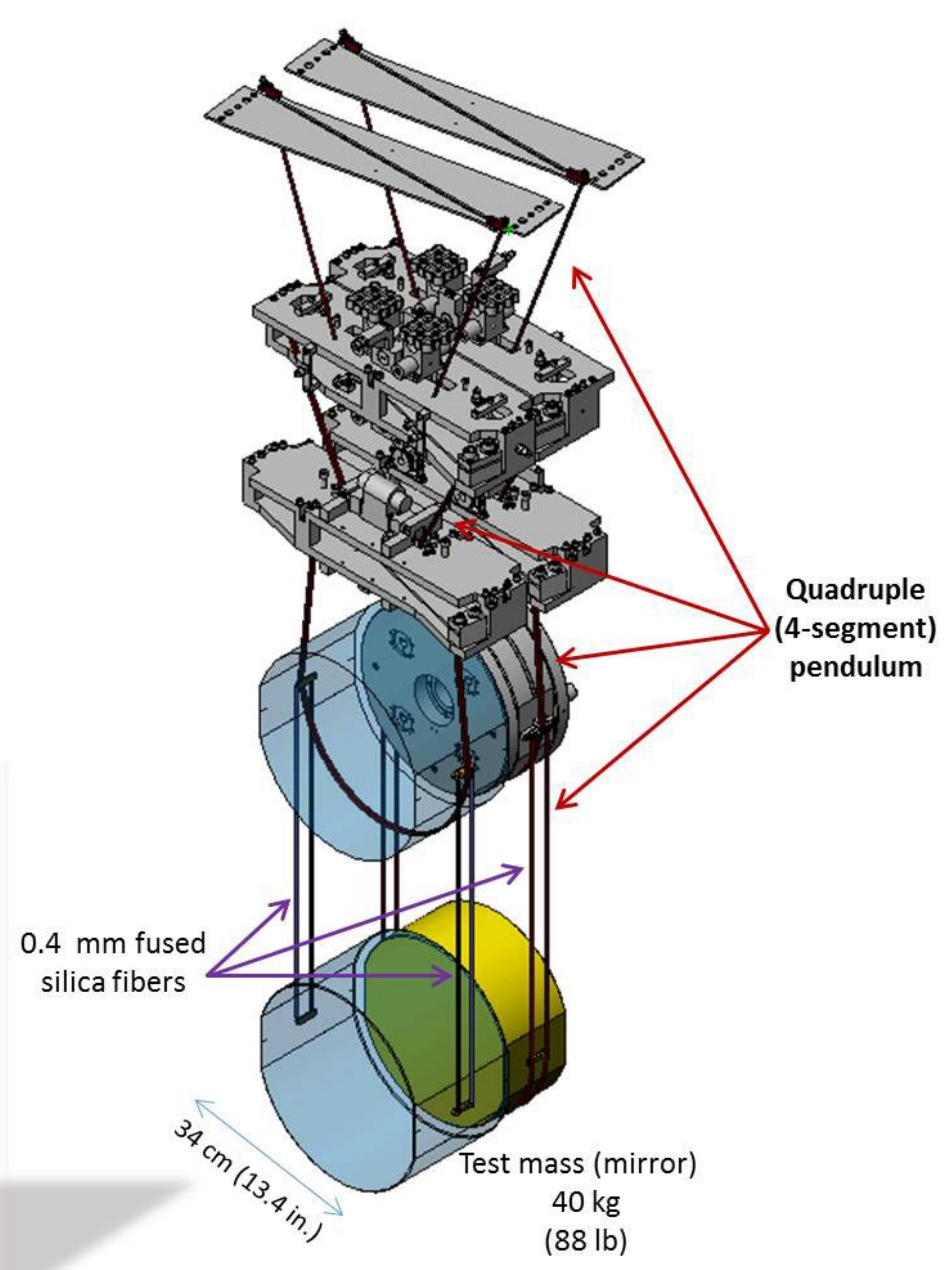


Strains from astrophysical sources ~10^{-21}
Measured over 4 km, ΔL ~ 10^{-18} m

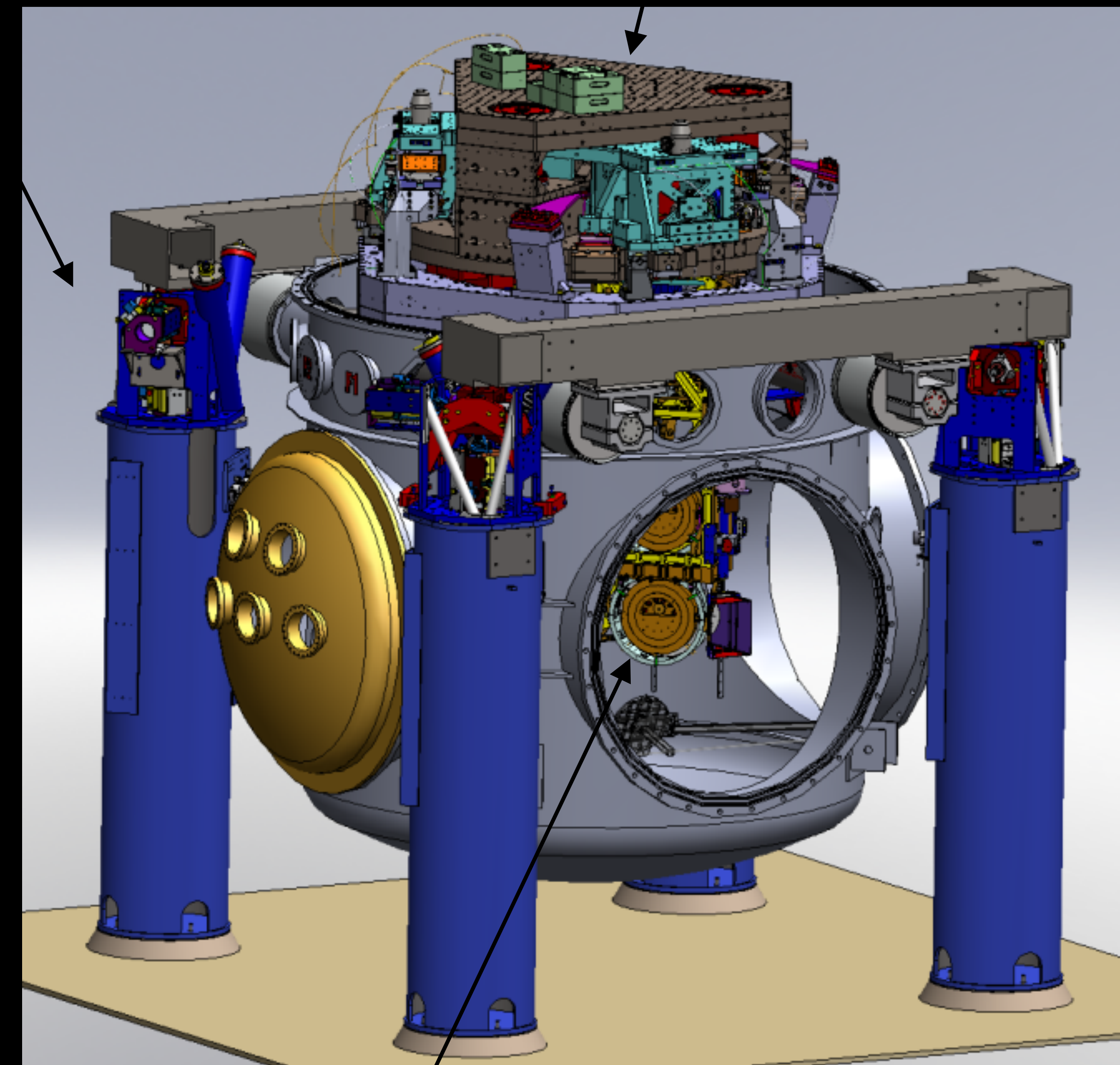
Observing GWs with interferometry

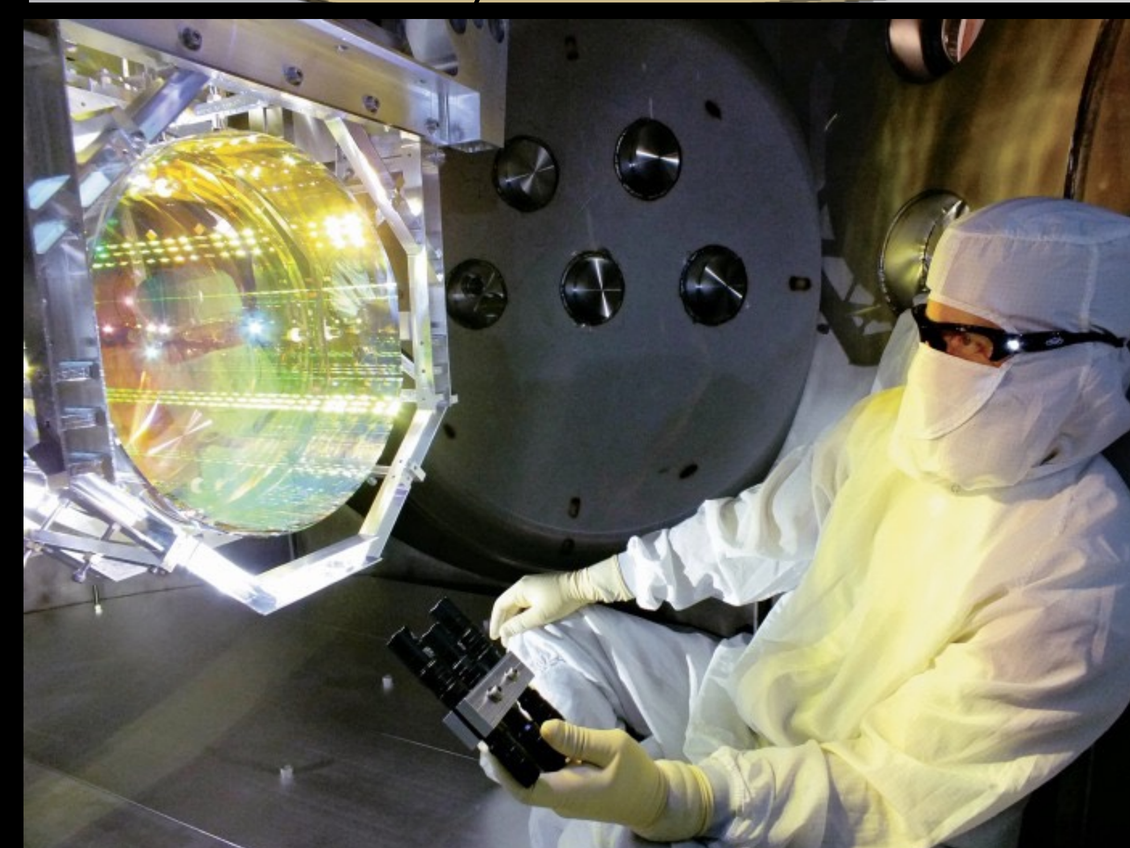


McIver



Seismic Isolation





A three interferometer network
and EM observer partners

LIGO/Caltech

Current Observing Run O3

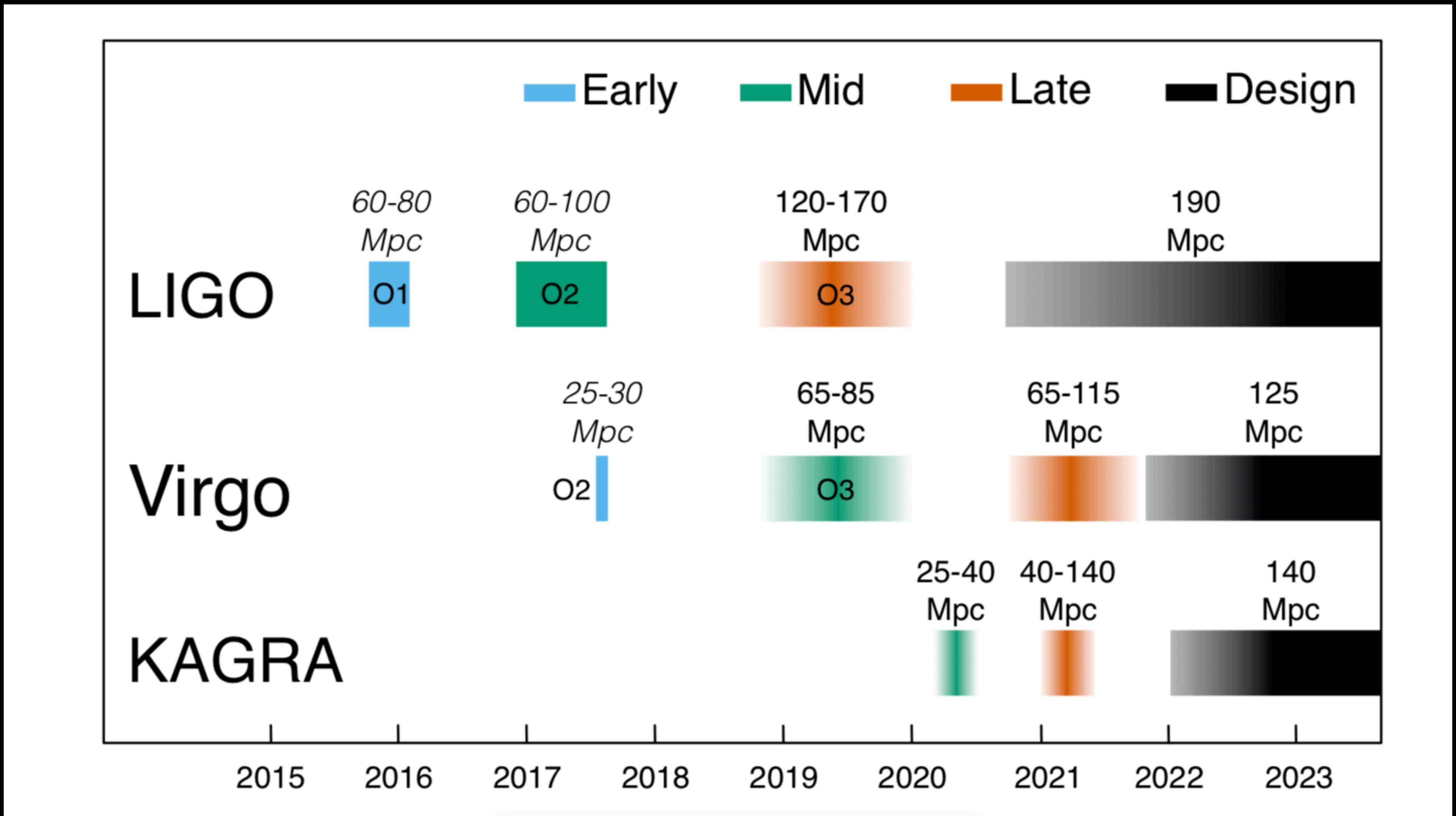
- April 2019 - May 2020
  - LIGO Hanford, LIGO Livingston, Virgo
  - KAGRA may join near end of run (!)

- ~~29~~ **30** candidate detections so far (and counting)
  - gracedb.ligo.org
  - ~1 per week

- Includes possible BNS and first NS-BH
  - plus lots of binary black holes

- "O3a" - first 6 months (ending soon)
  - Target to publish O3a catalog around April of 2020

GW Detector Timeline



Detections: 3 8 50 150 ~400

1 / week 3 / week 1 / day

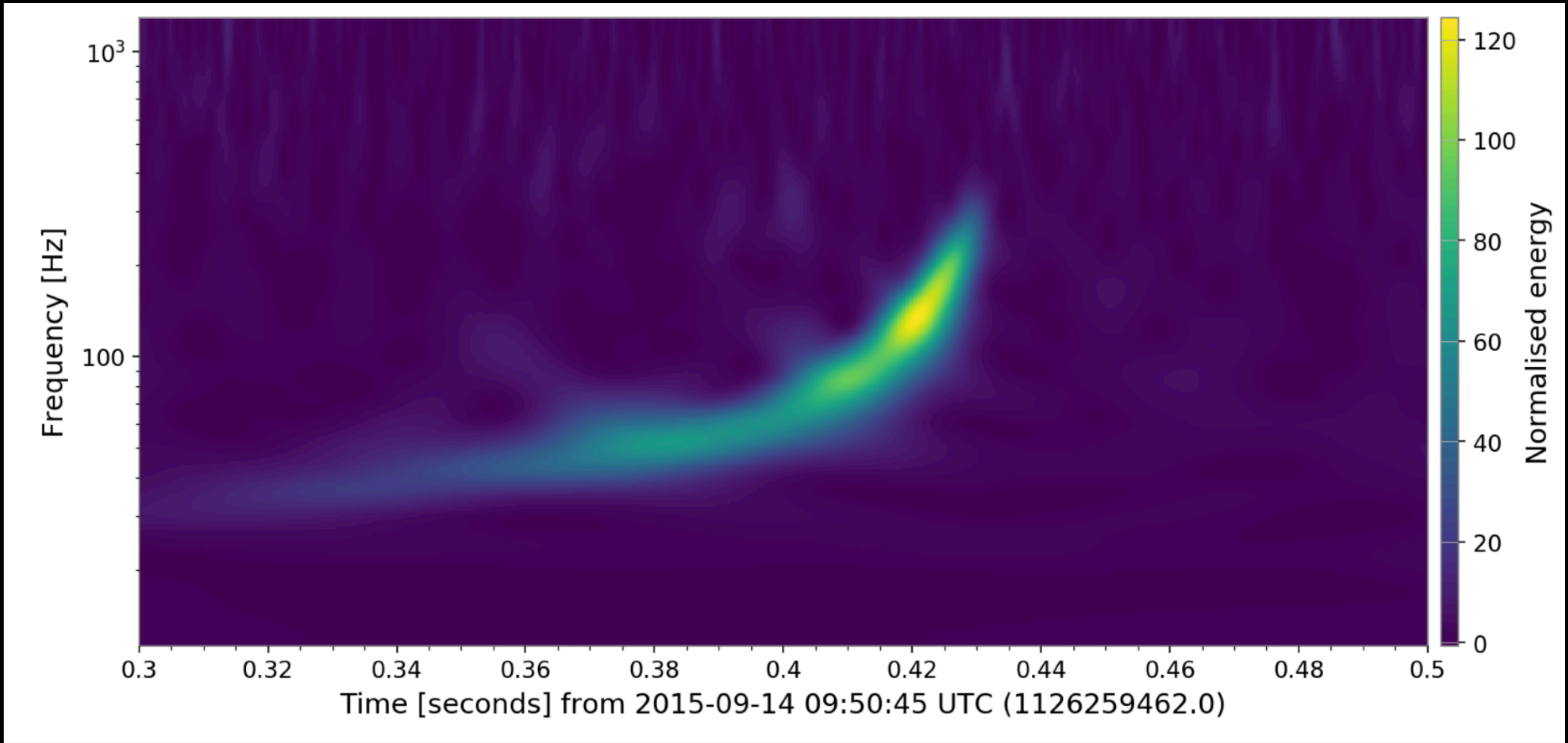
https://arxiv.org/abs/1304.0670

Gravitational Wave Bursts

Discover & Characterize transients without templates

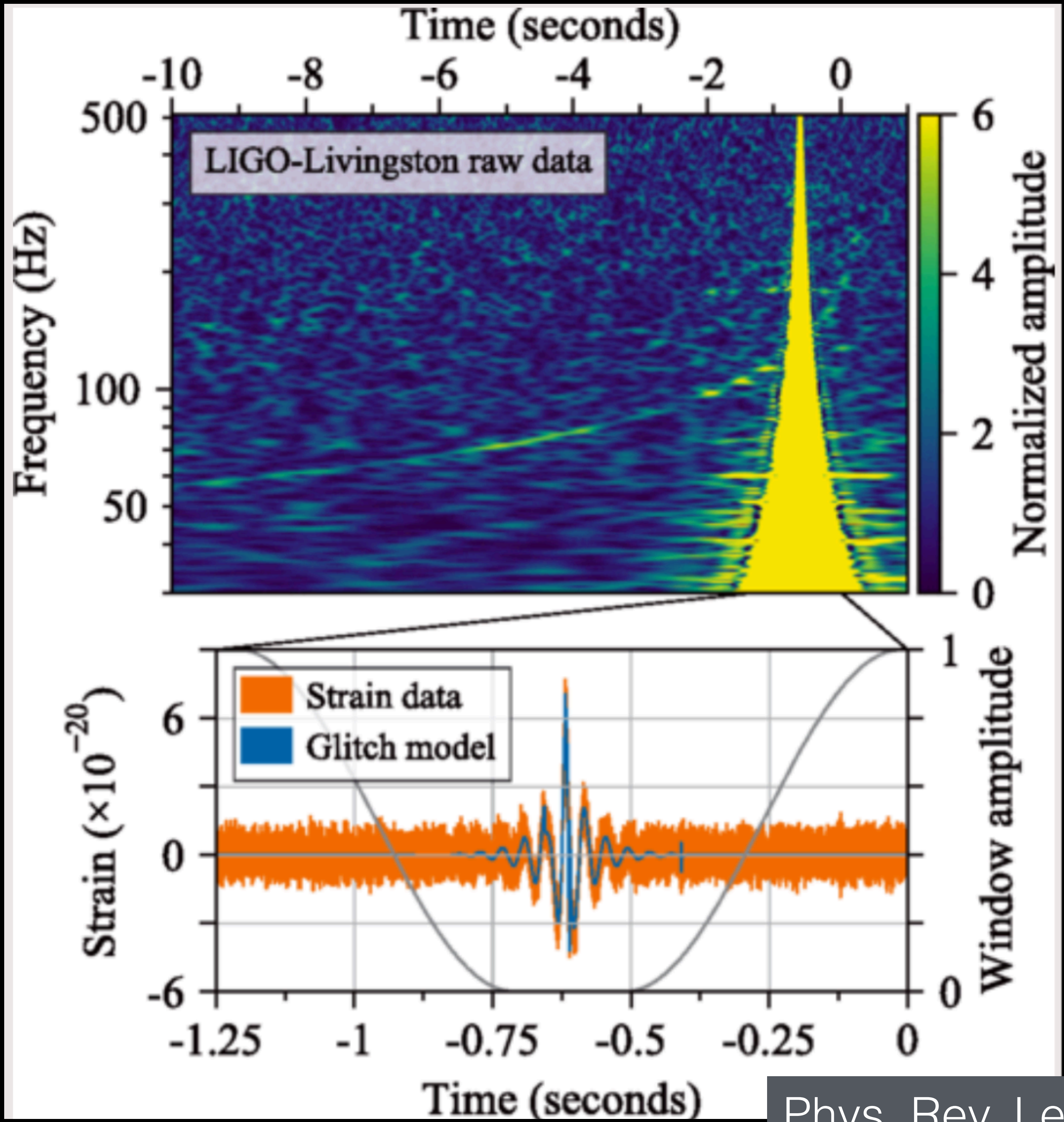
Work in time-frequency domain (mostly)

Use “coherence” between multiple detectors



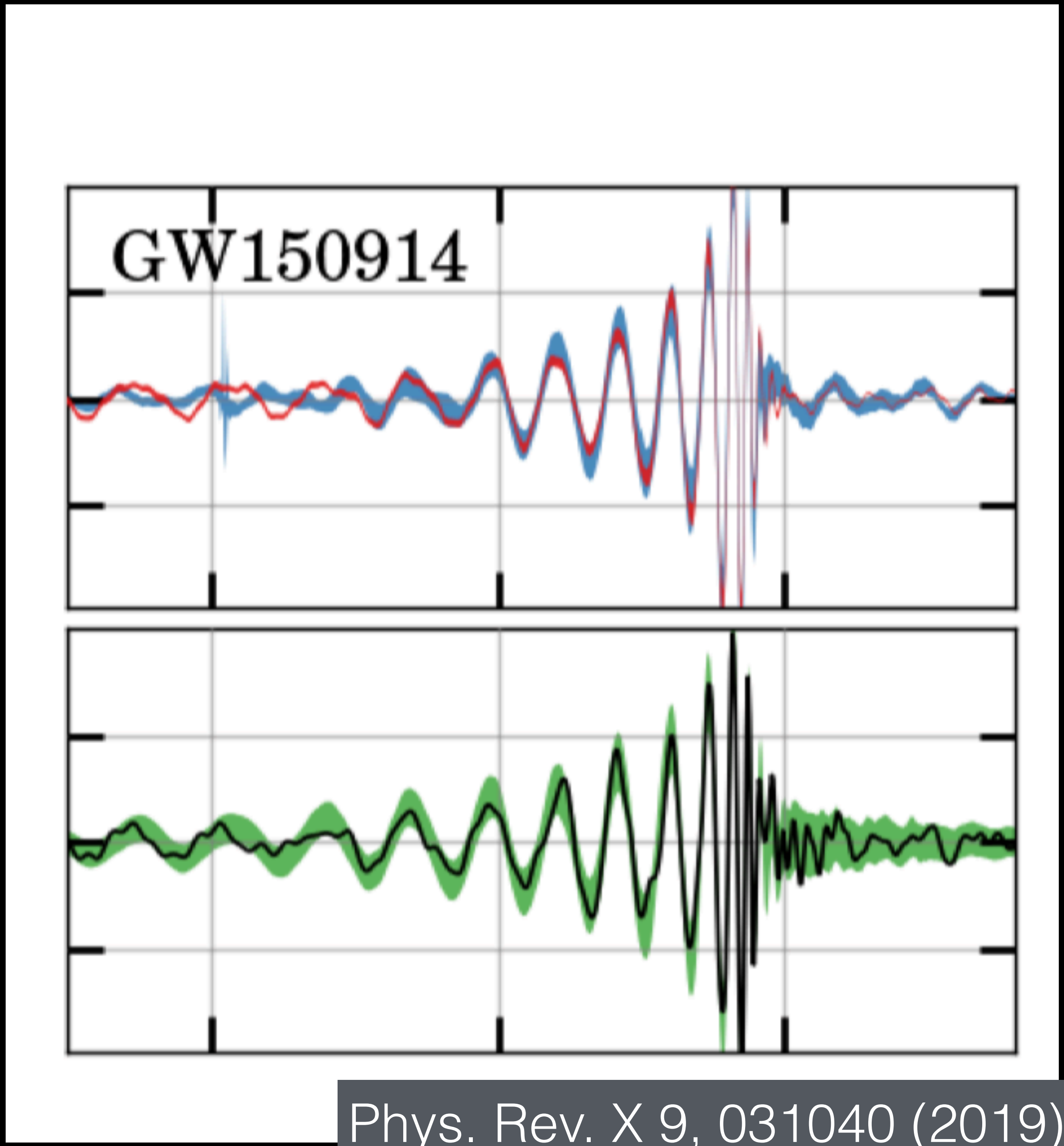
Waveform Reconstructions

Glitch fitting for data cleaning



Phys. Rev. Lett. **119**, 161101

Compare data and models



Phys. Rev. X 9, 031040 (2019)

Better modeling of data —> More sensitive detections

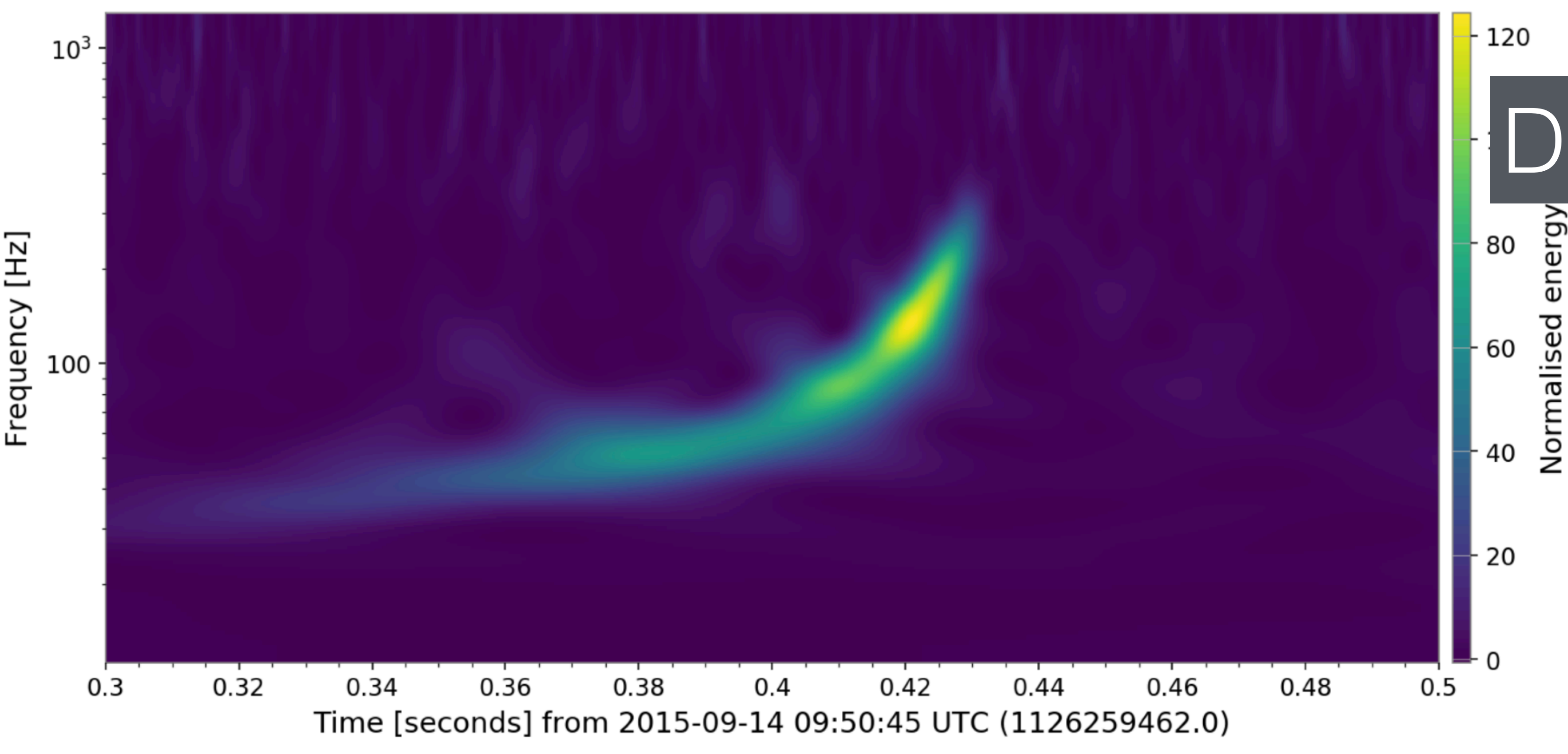
Searching for GW signals usually involves looking for "loudest" signal + cuts to remove glitches

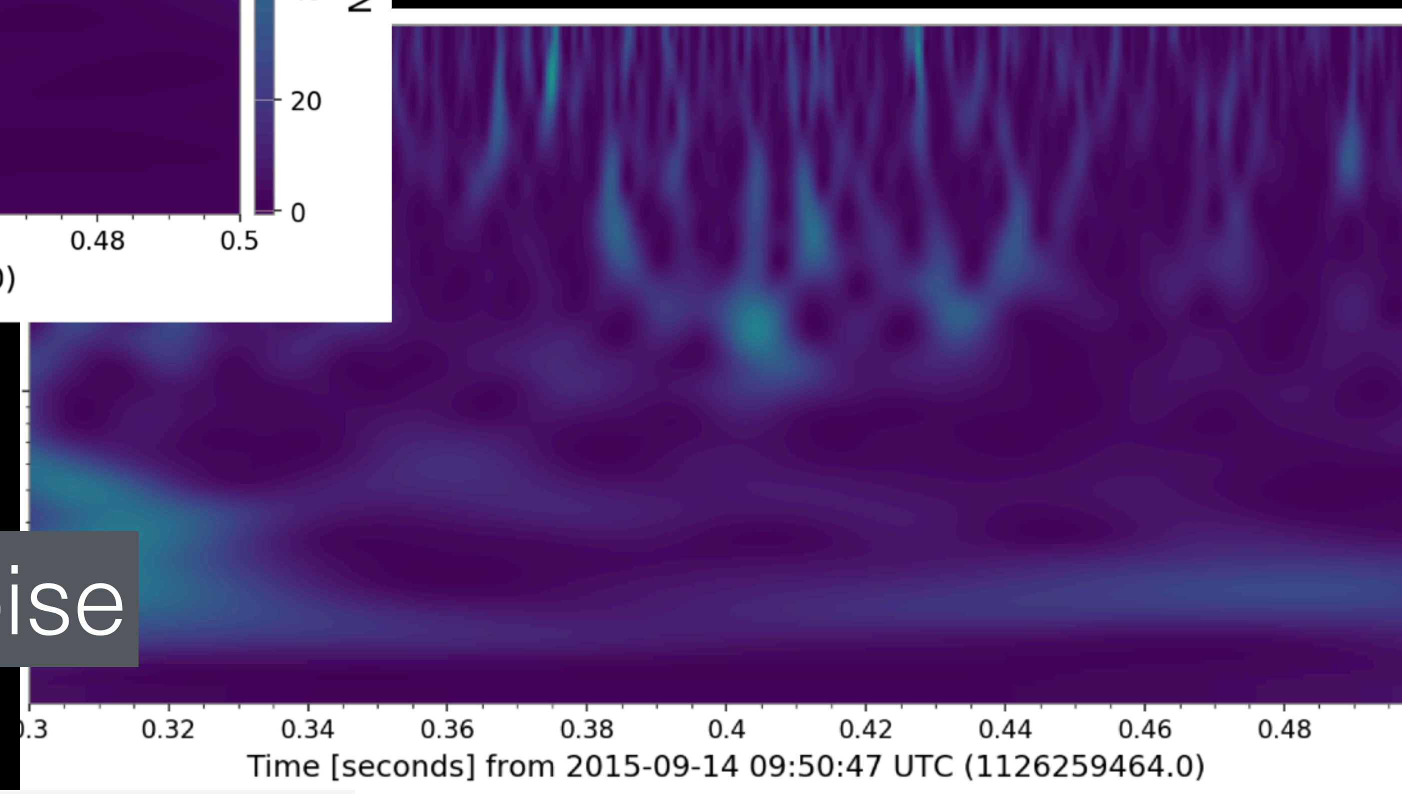
- e.g. ranking statistic scales with SNR
  - Louder is better

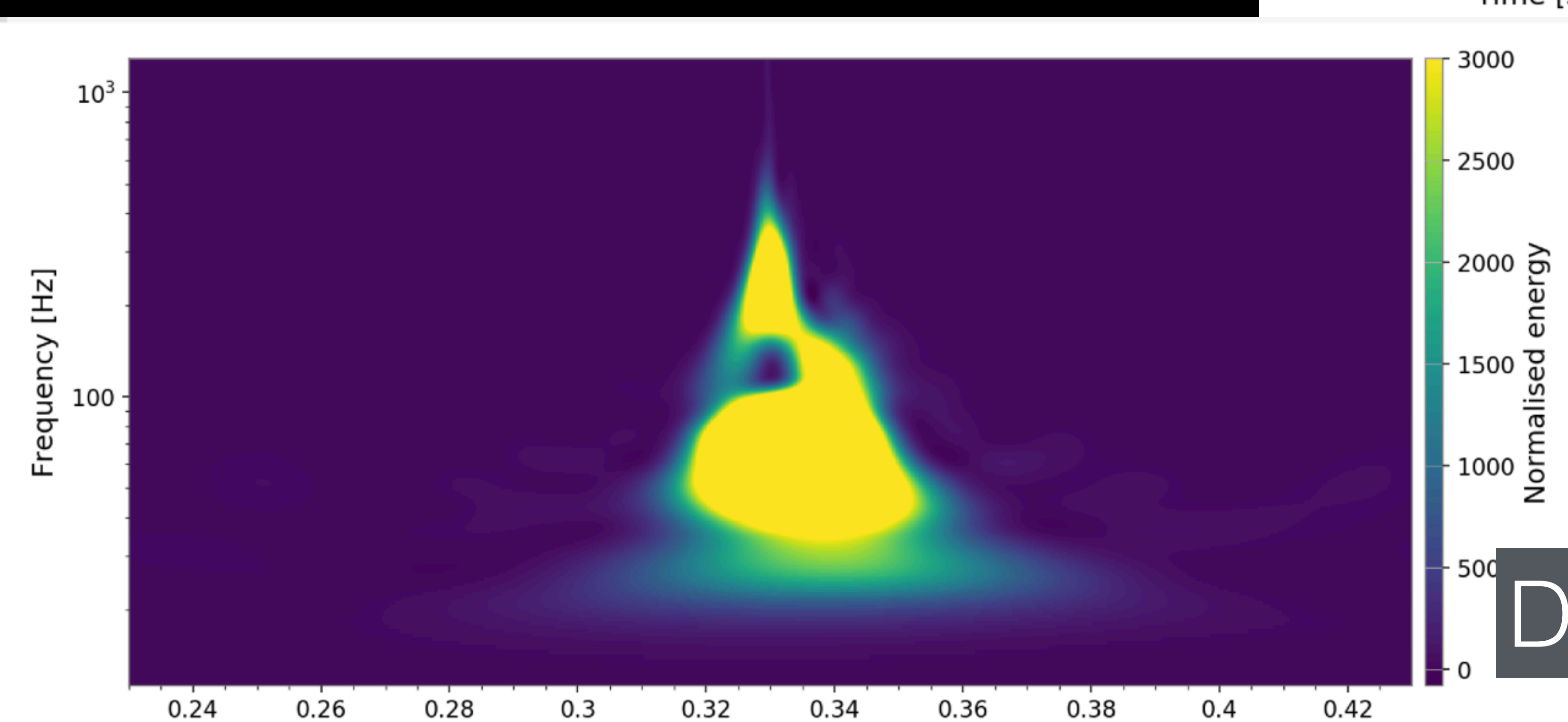
Works well if the detector noise is Gaussian,
but can fail when data contain artifacts (glitches)

Instead, can use Bayesian model selection to choose between competing models:

- Data are Gaussian noise
- Data are Gaussian noise + a glitch
- Data are Gaussian noise + a signal


Data contain a signal
Frequency [Hz]
10^3
100
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
Time [seconds] from 2015-09-14 09:50:45 UTC (1126259462.0)
Normalised energy
120
80
60
40
20
0

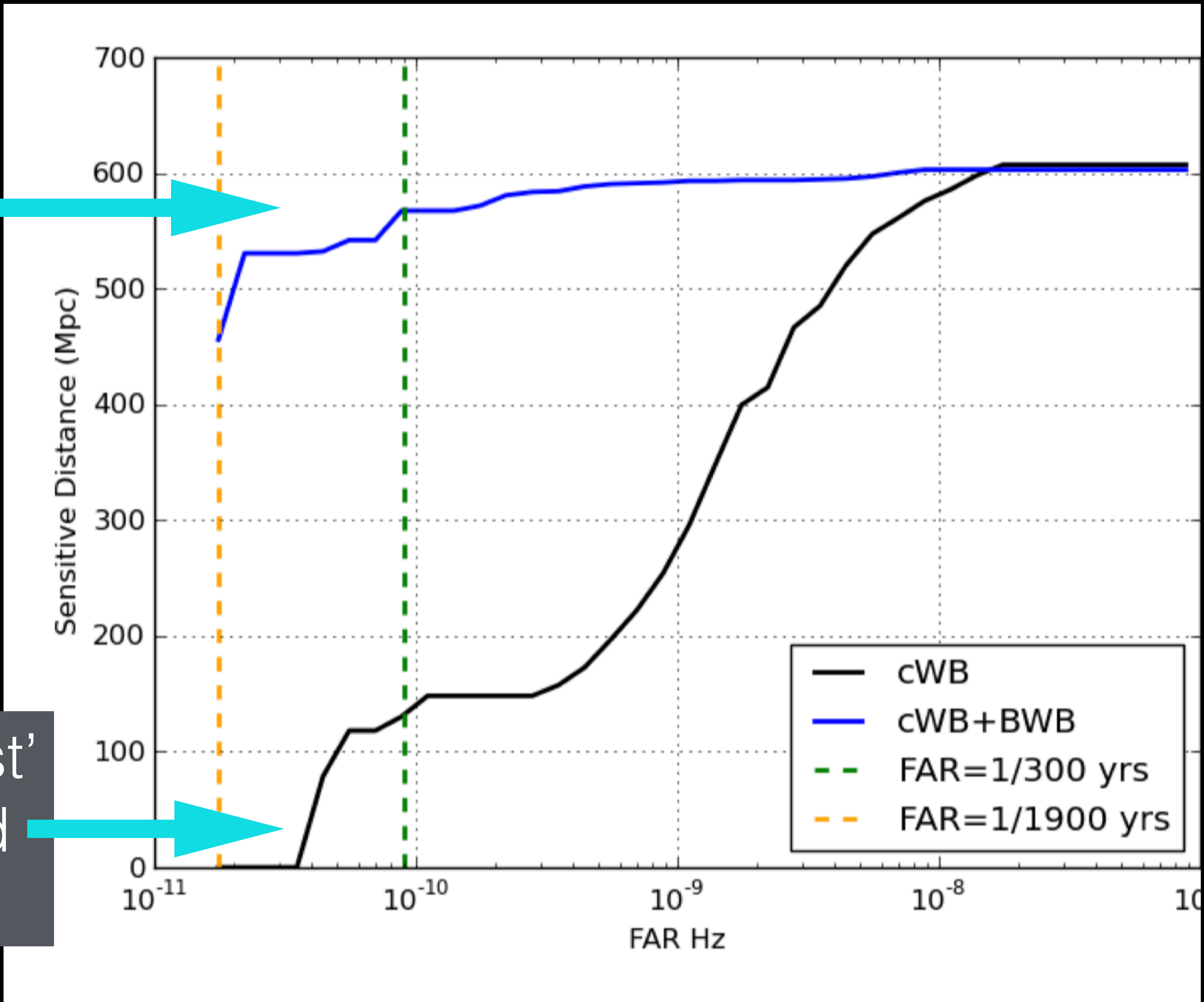

Data are Gaussian noise
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
Time [seconds] from 2015-09-14 09:50:47 UTC (1126259464.0)


Data contain a glitch
Frequency [Hz]
10^3
100
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
Normalised energy
3000
2500
2000
1500
1000
0

Bayesian model selection for burst searches

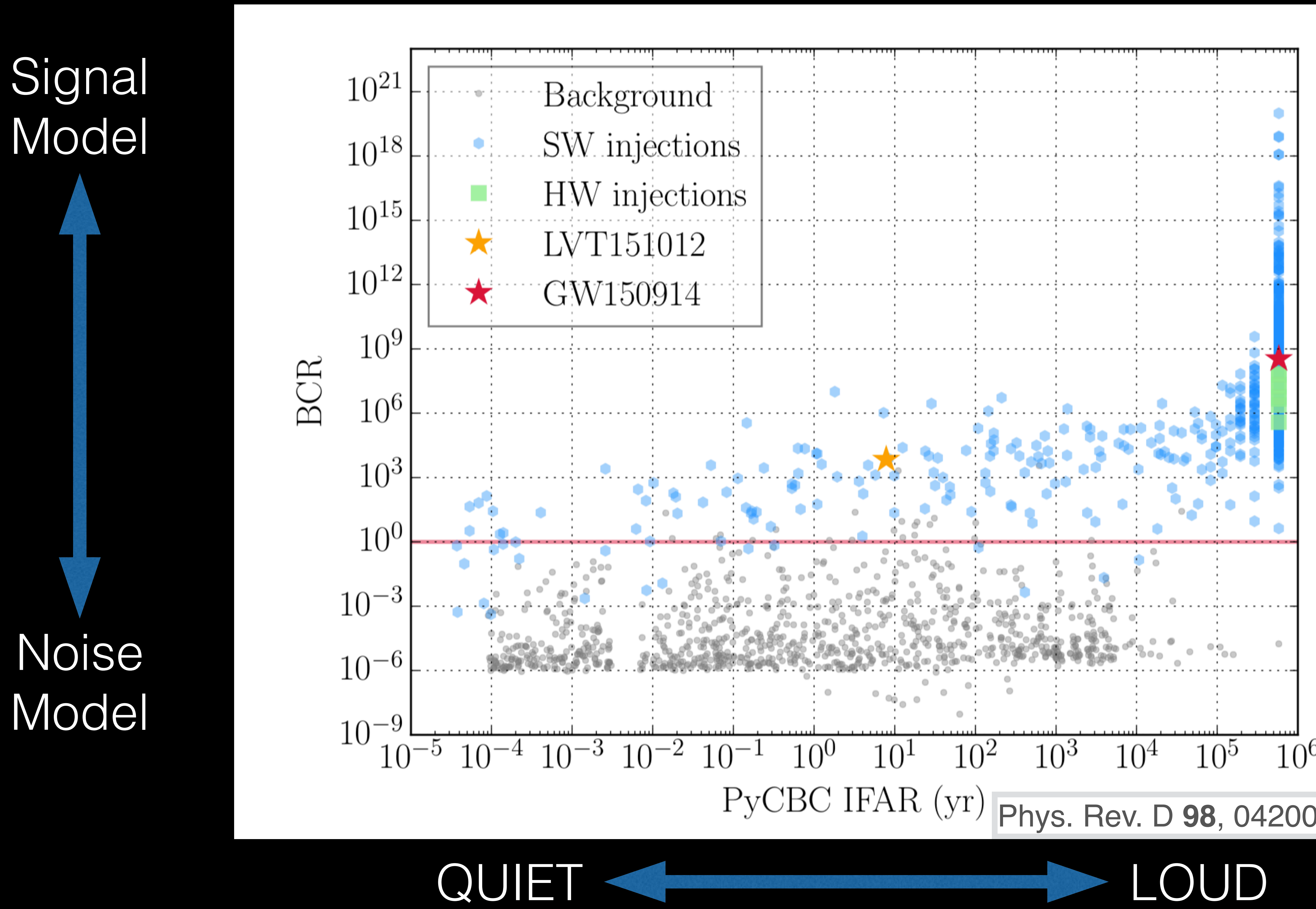
Search that models data+glitches does better

Search for 'loudest' event gets fooled by glitches

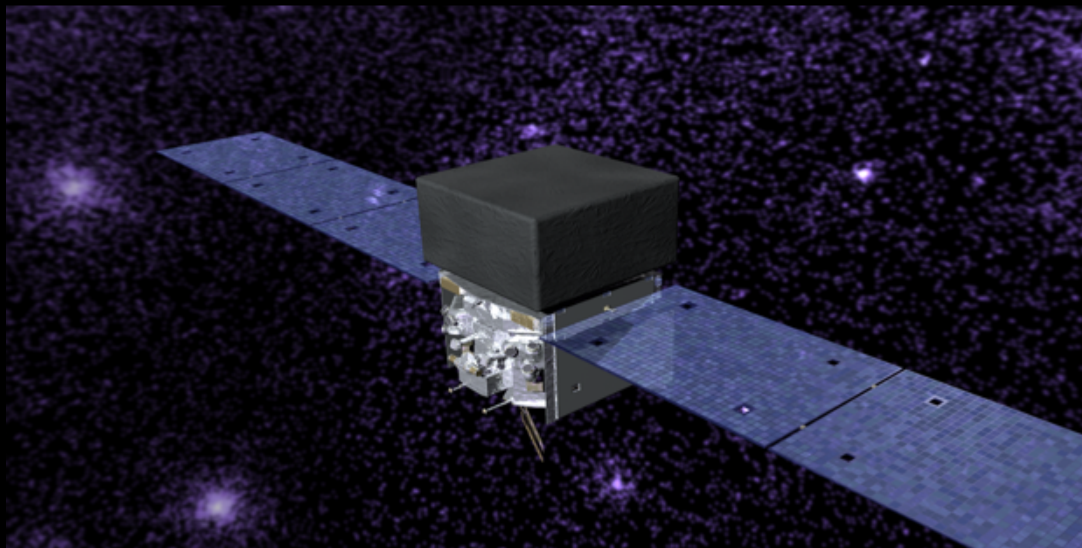


Phys. Rev. D **93**, 022002

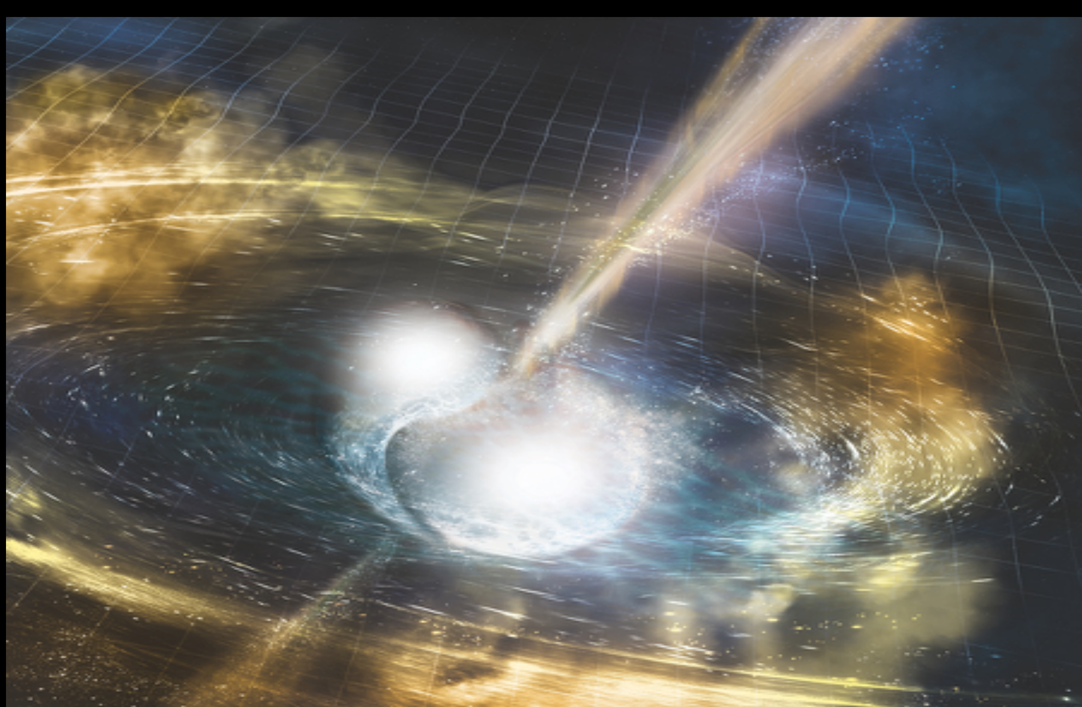
Bayesian model selection for matched filter searches



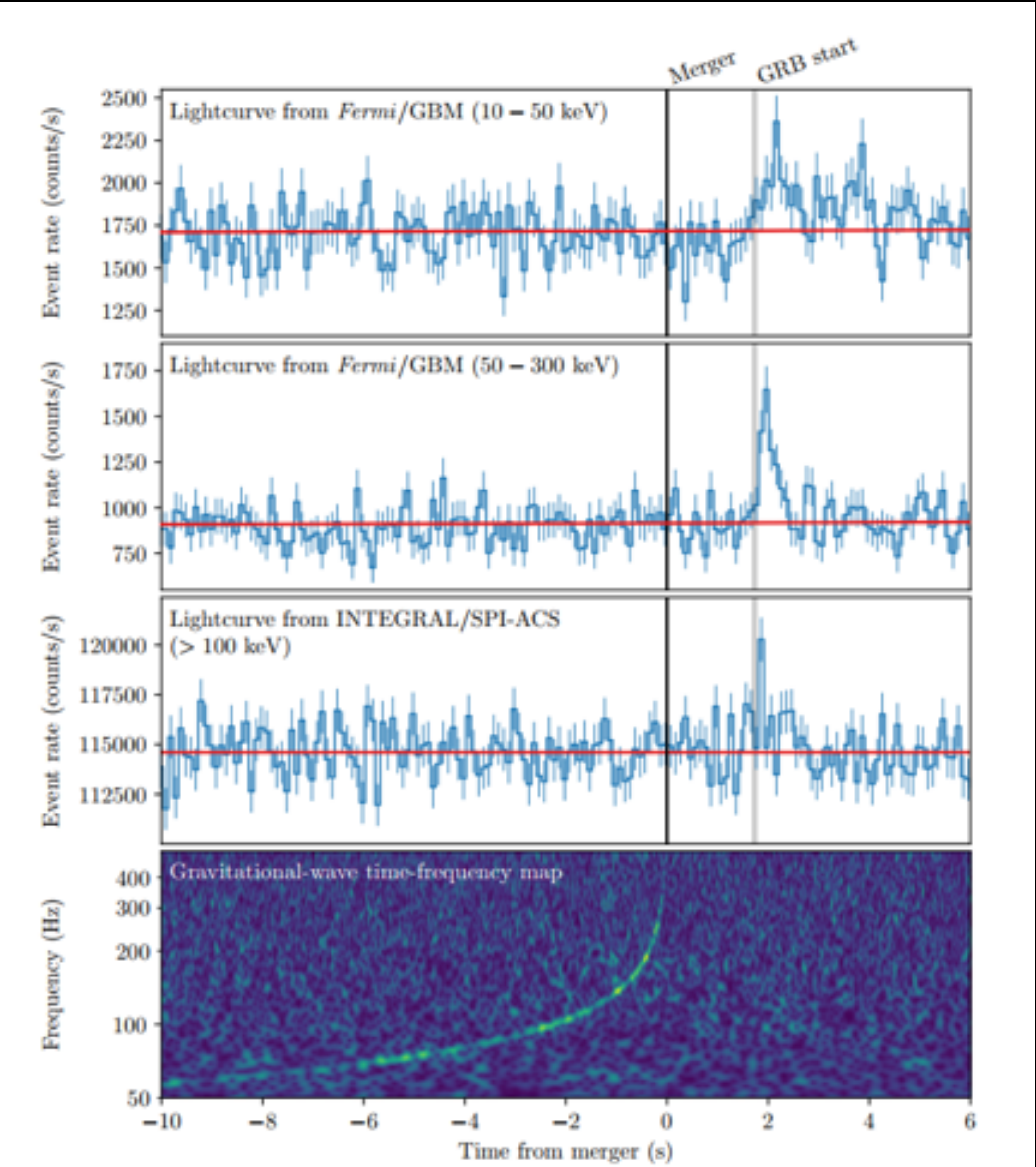
Phys. Rev. D **98**, 042007



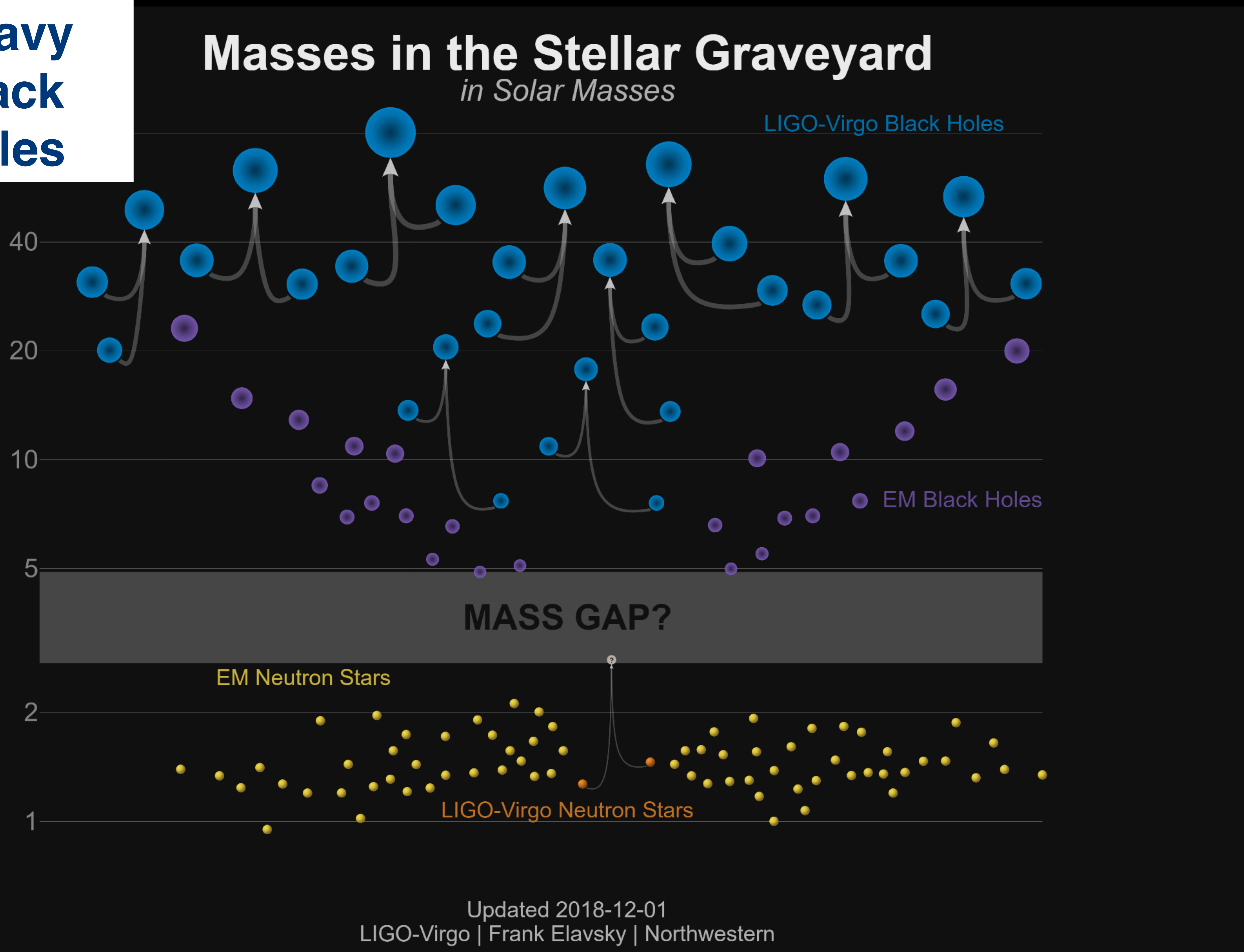
Credit: NASA



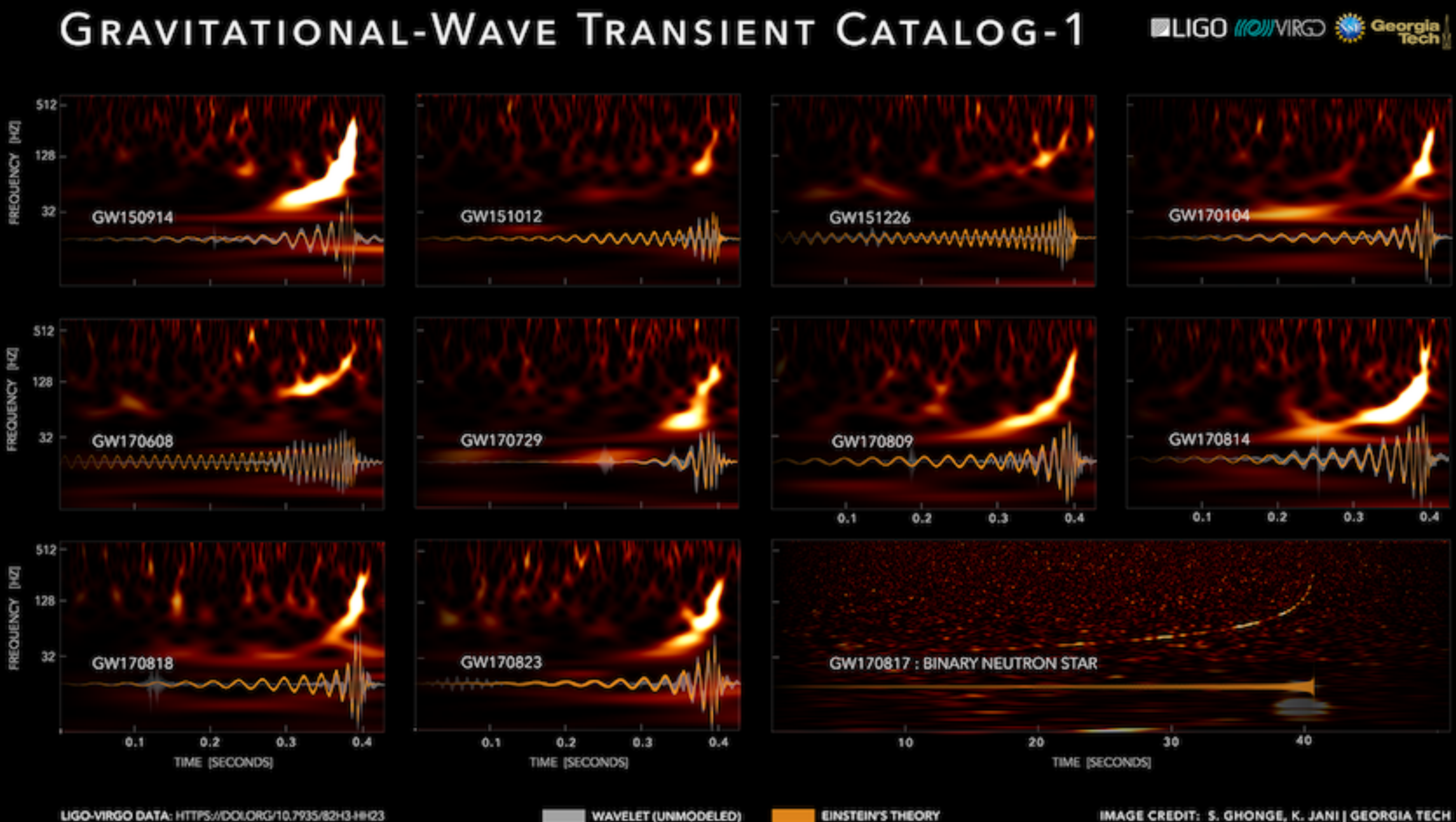
Credit: NSF/LIGO/Sonoma State University/A. Simonnet



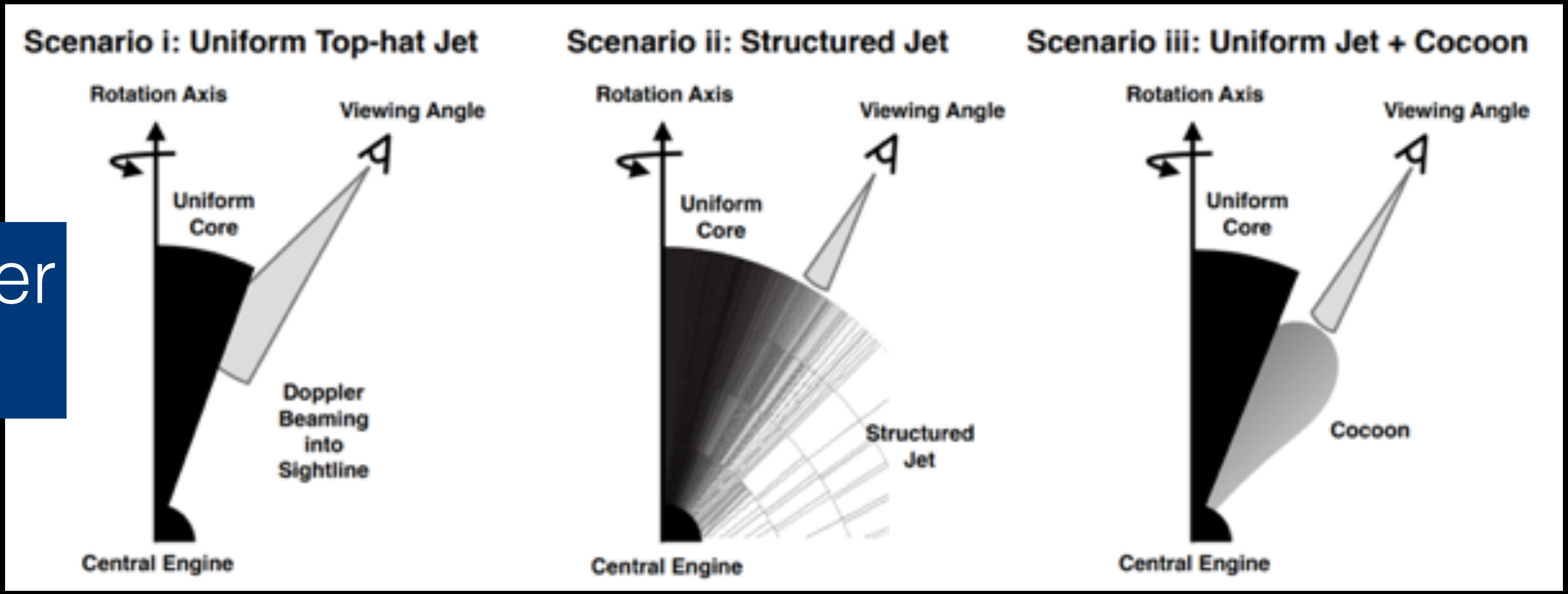
Heavy black holes



GWTC-1

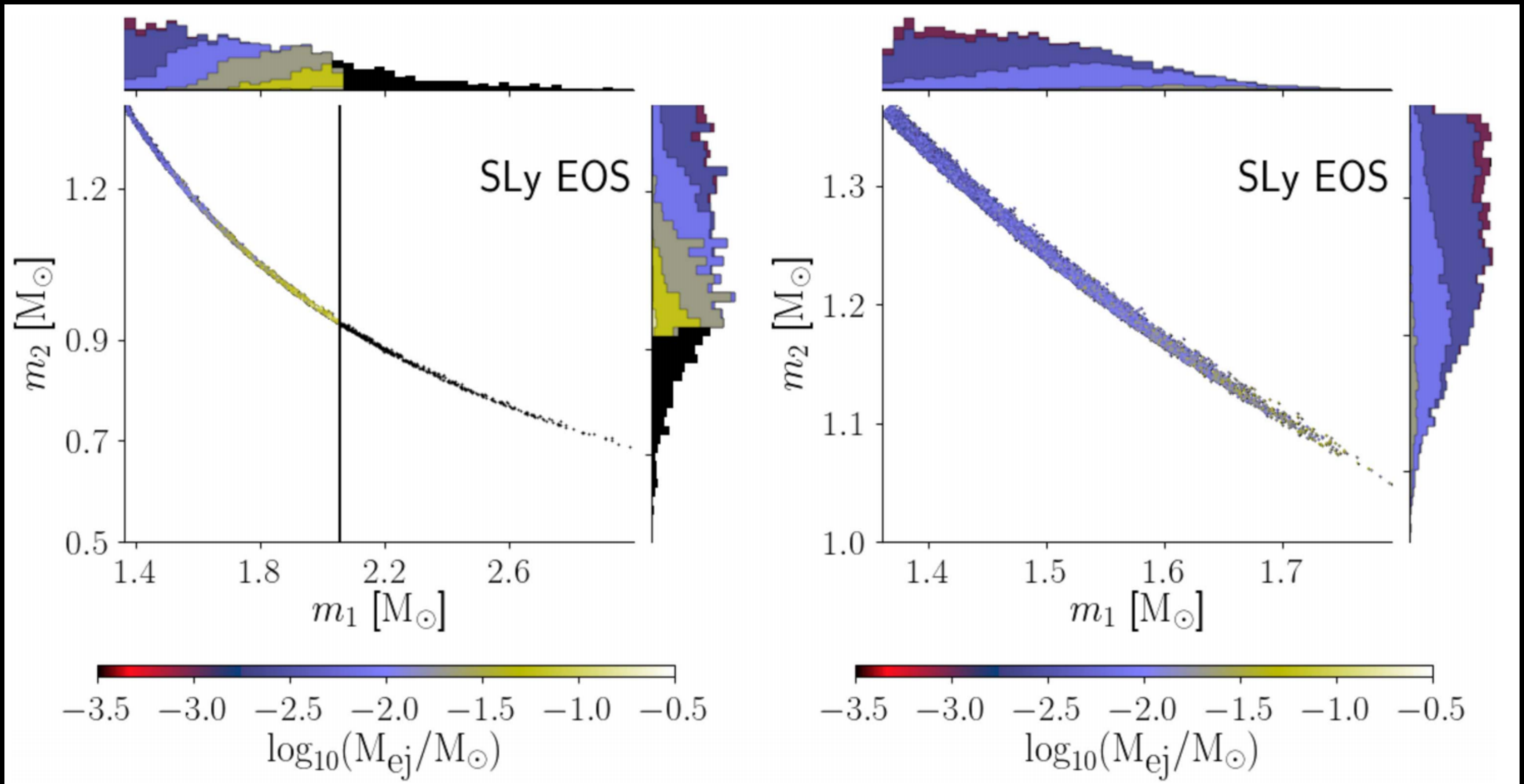

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1 0.2 0.3 0.4
10 20 30 40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Multi-messenger astrophysics



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) ApJ Lett. **848**, L13

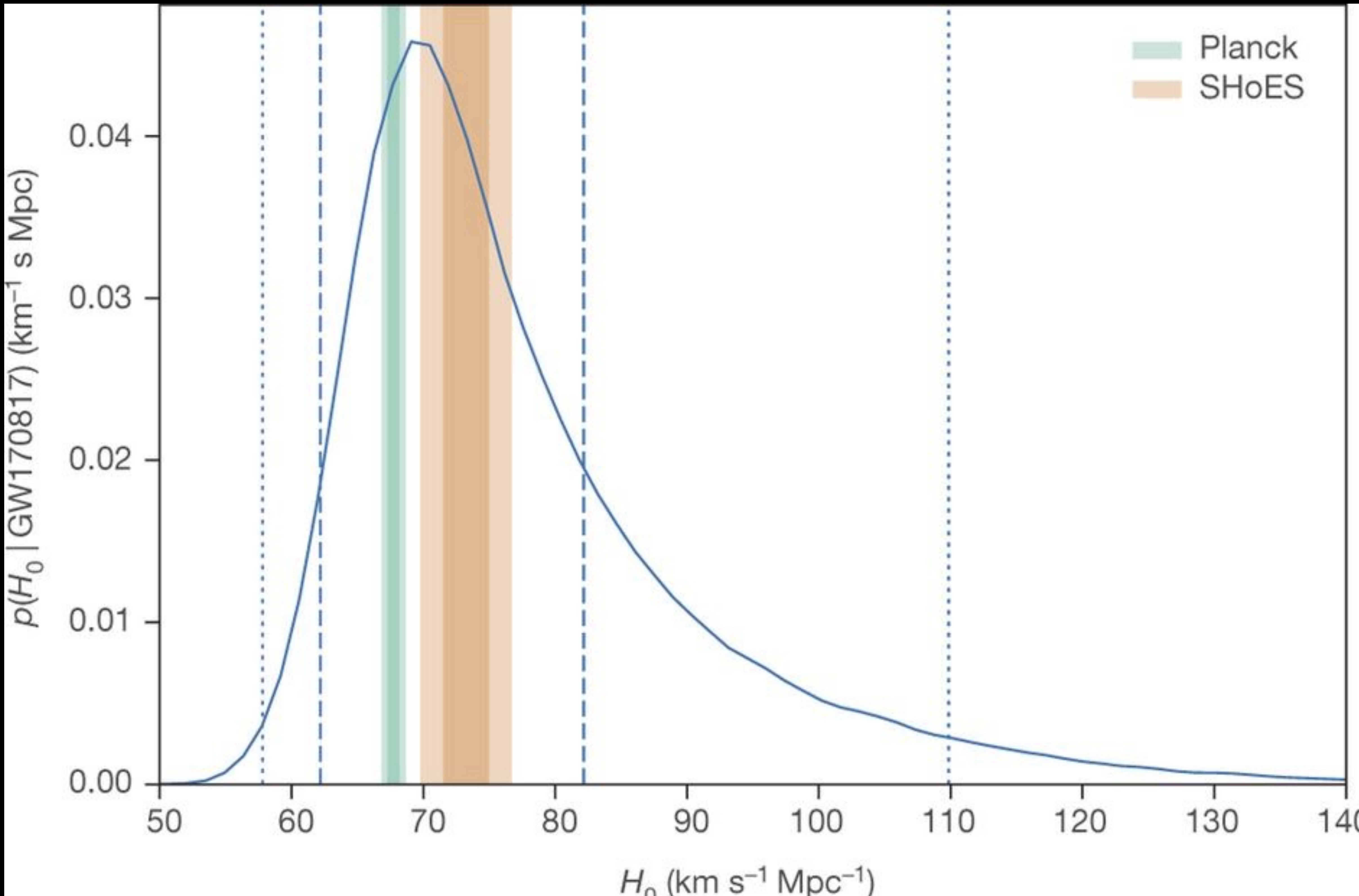
Jets and Outflows



Neutron Star Equation of State

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), The Astrophysical Journal Letters, 850:L39 (13pp), 2017 December 1

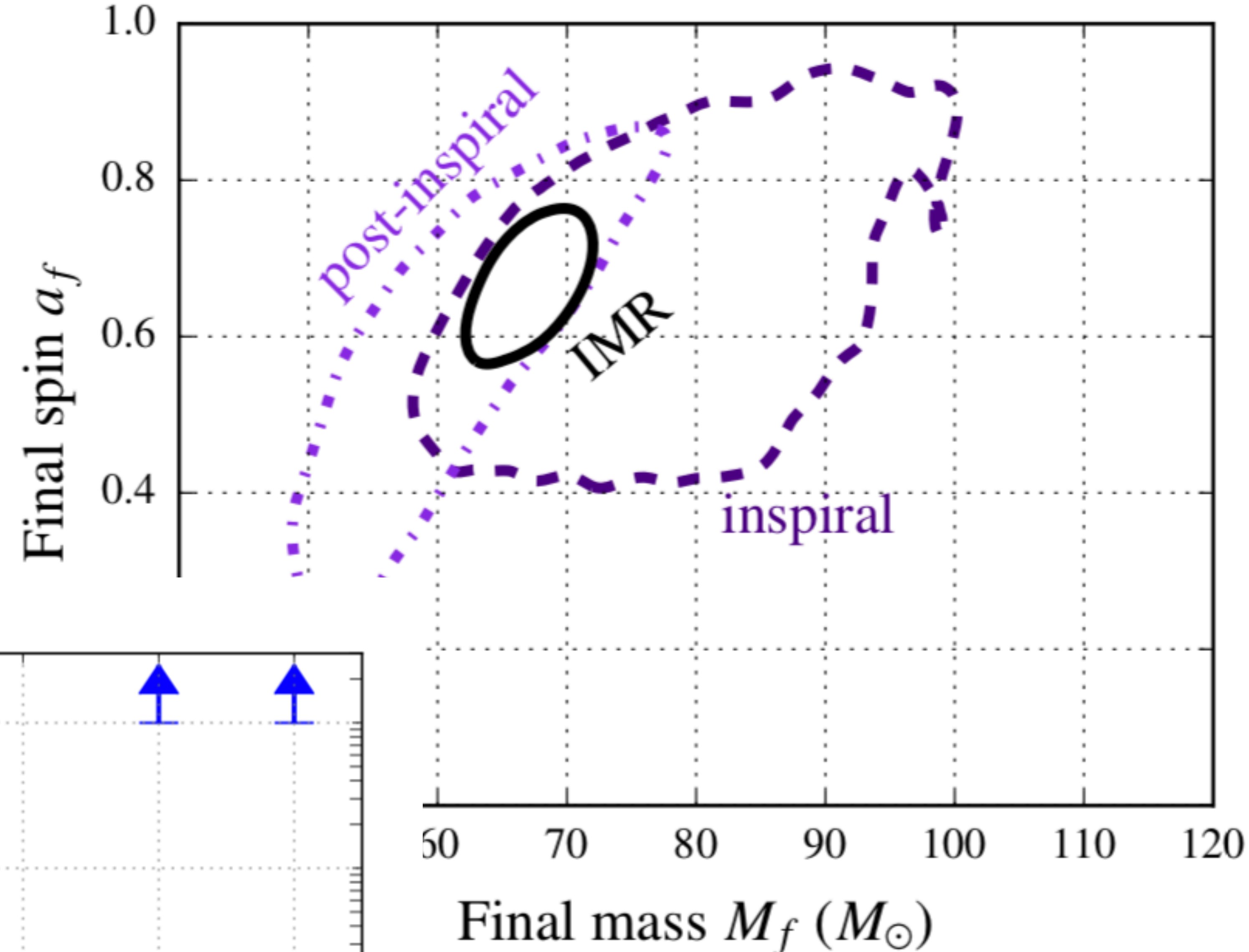
Measure the Hubble Constant

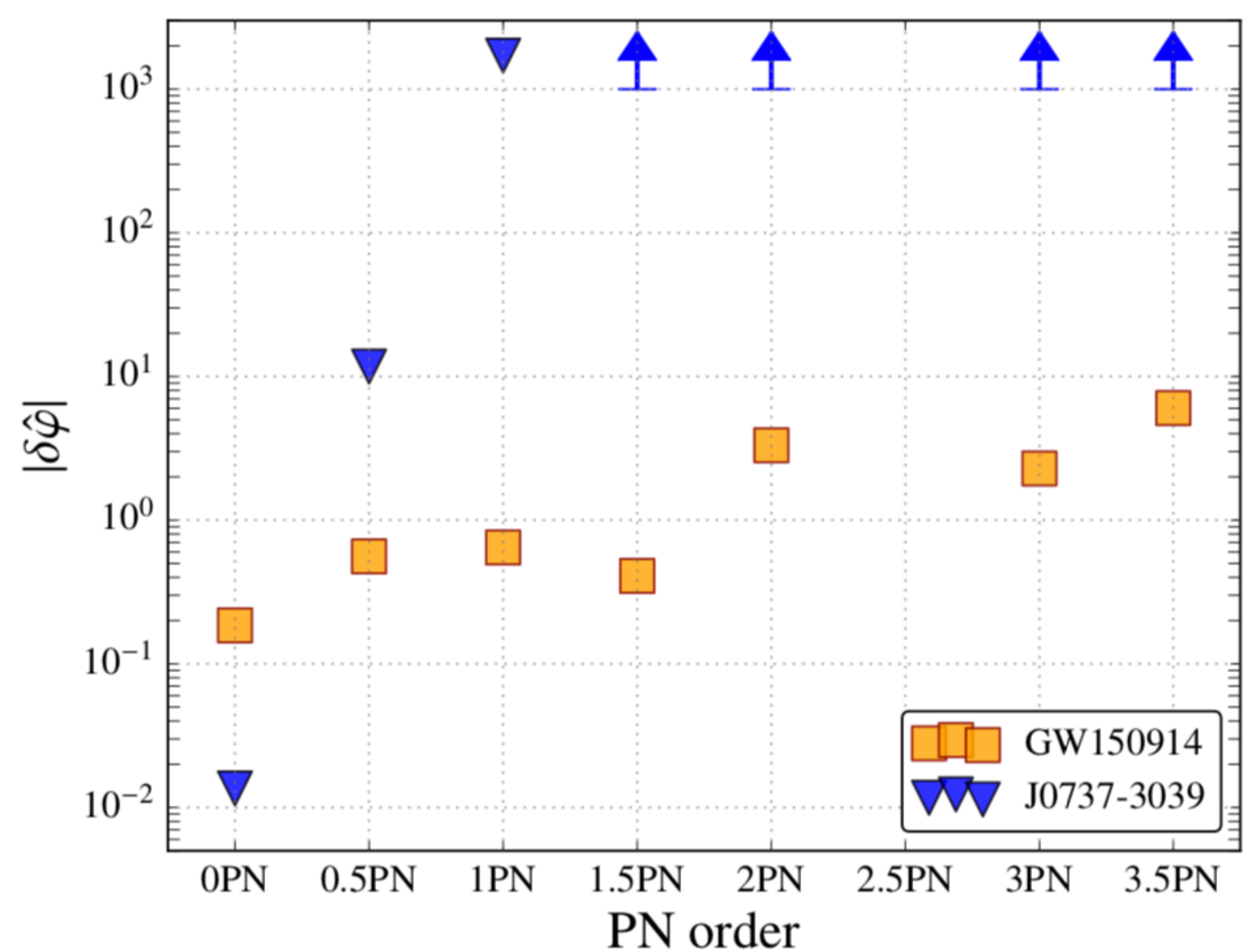


B. P. Abbott *et al.* Nature 551, 85–88, 2017

Test General Relativity in strong gravity

Measure BH ringdown

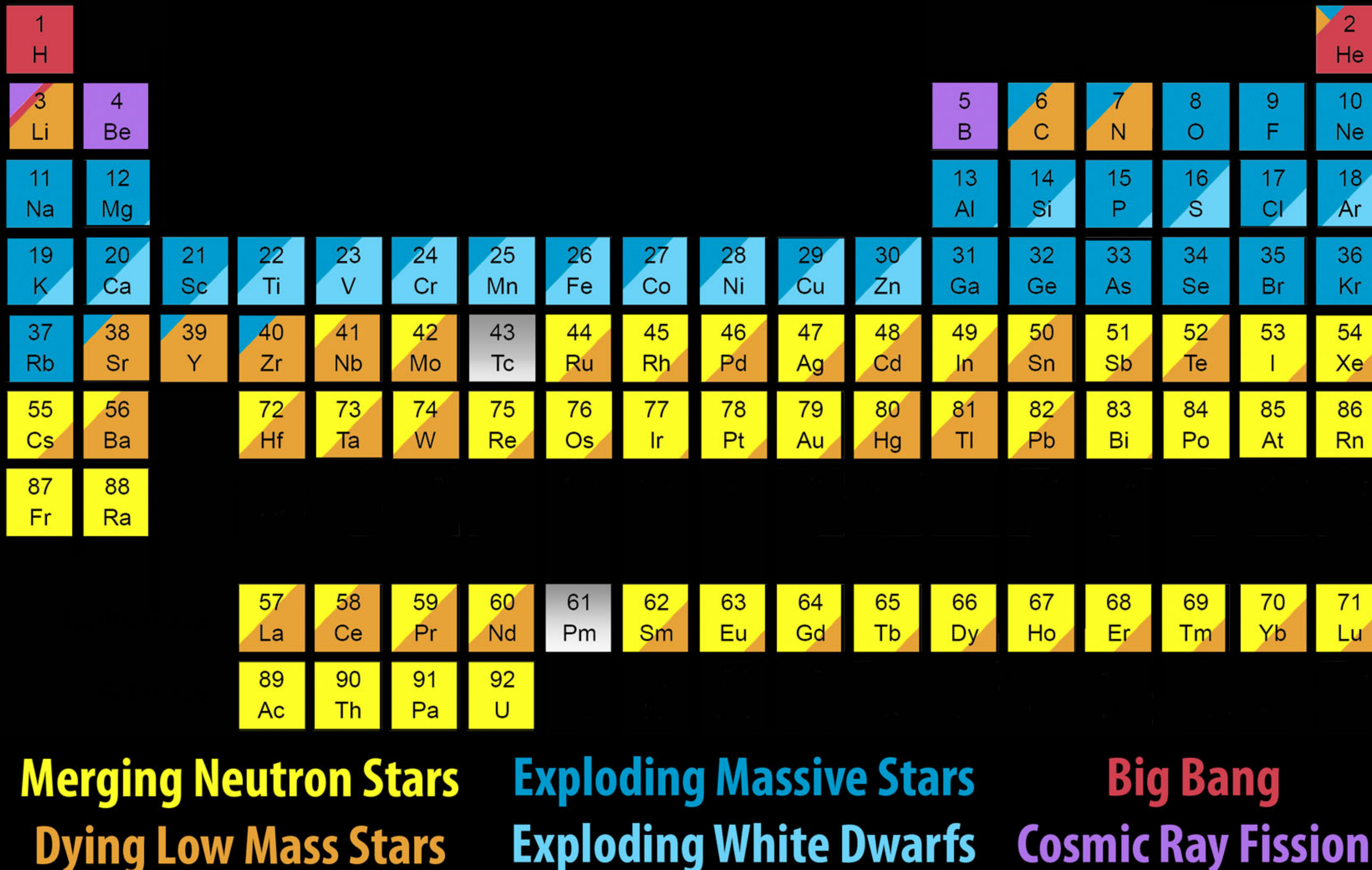




Measure waveform phase evolution

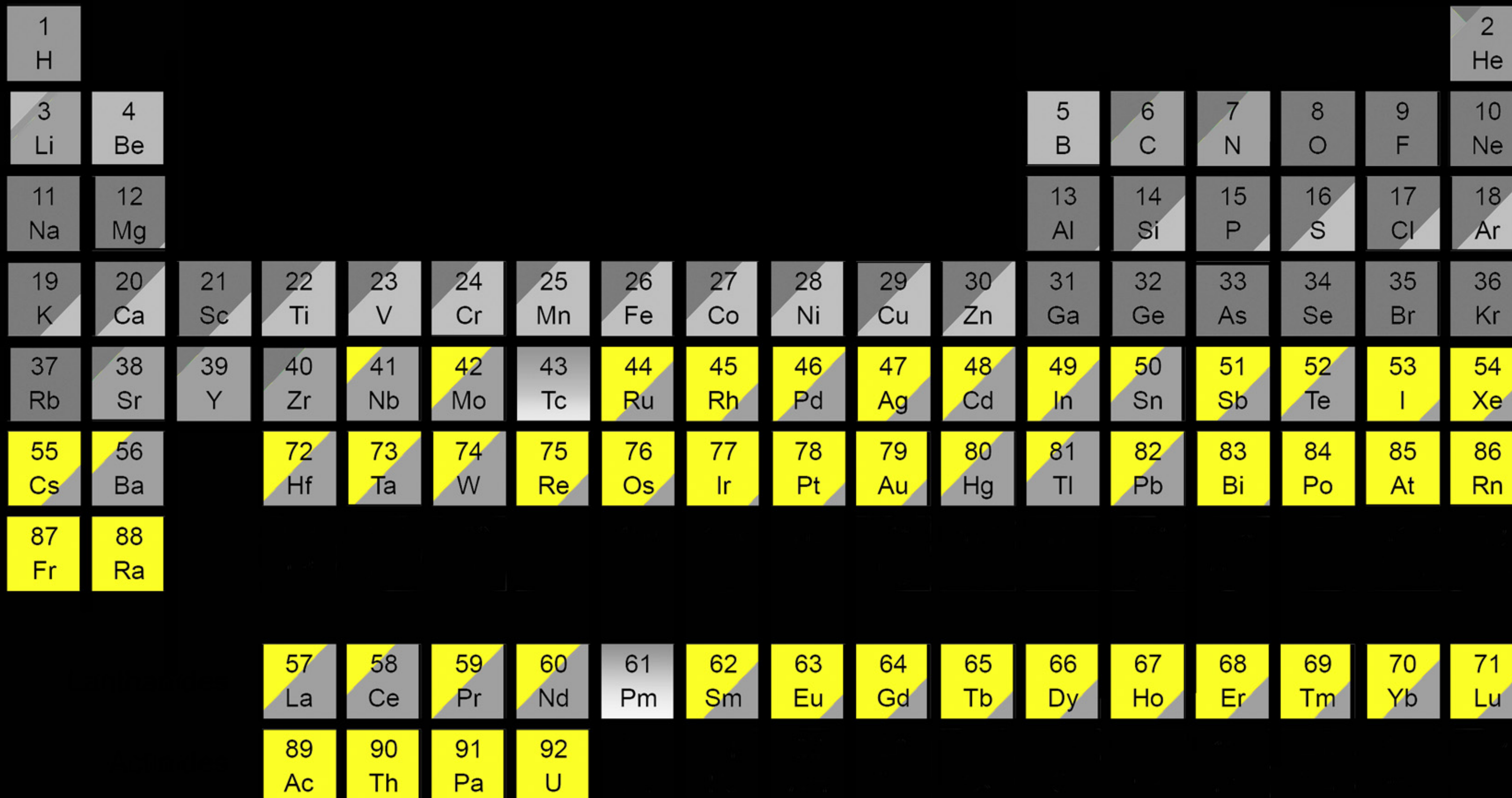
Phys. Rev. Lett. **116**, 221101 – 2016

Binary neutron star mergers form heavy elements



Based on graphic created by Jennifer Johnson

Binary neutron star mergers form heavy elements



Yellow: Formed by Merging Neutron Stars